Distributed Embedded
Systems Group – CCS

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Towards the Tactile Internet: Low Latency Communication for Connected Cars

Falko Dressler

Outline

- Coordinated Automated Driving
- Towards the Tactile Internet
- Vehicular Networking
- Beaconing and Vehicular Ad Hoc Networks
- Case Study: Platooning
- Performance Evaluation

Coordinated Automated Driving

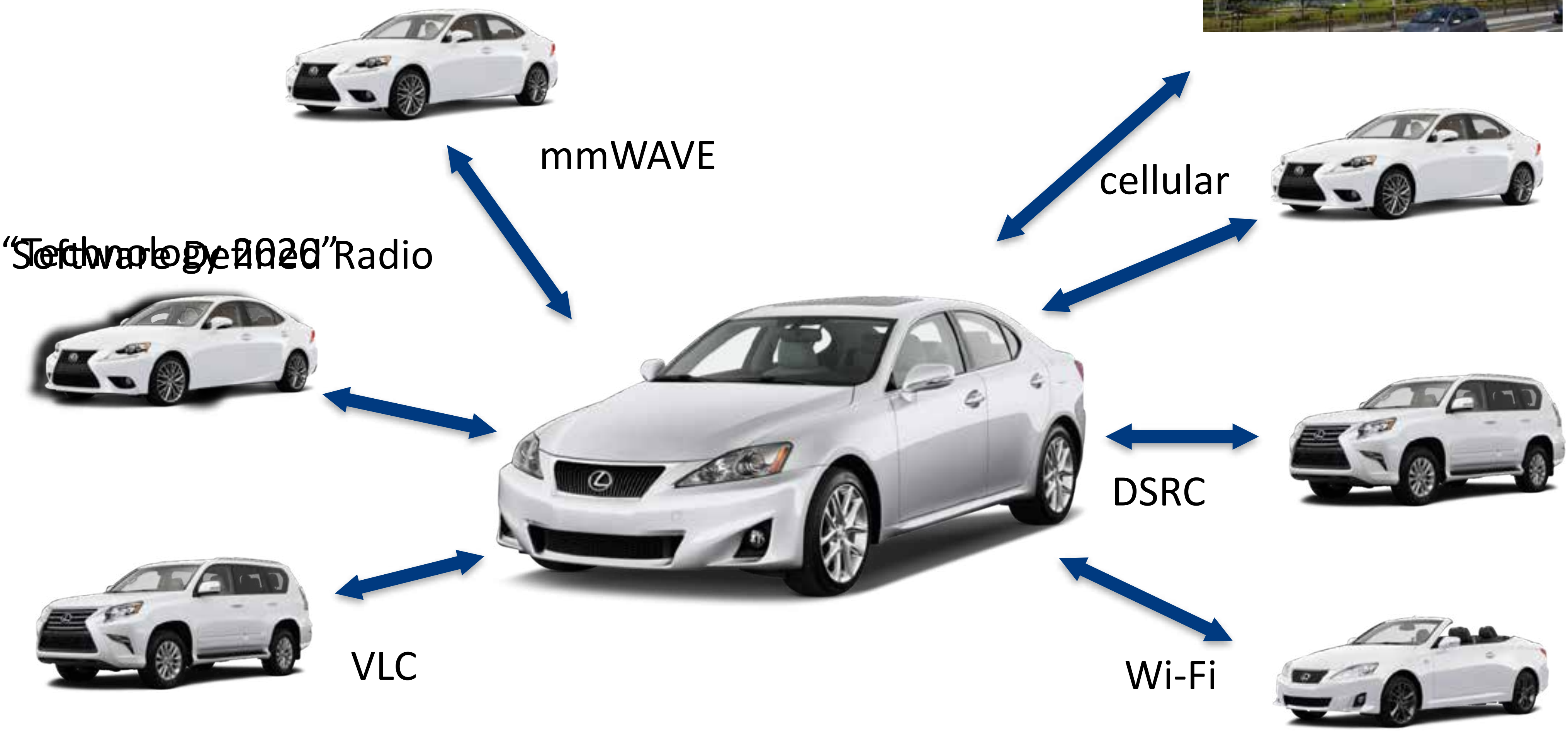
Towards Autonomous Driving

Inter-Vehicle Networking for Situation Awareness

Illustrations: C2C-CC

Towards Heterogeneous Vehicular Networks

- Many communication channels available
  - Which to pick when?



Standardization and Open Research

- Dedicated spectrum for inter-vehicle communication
  in Europe (5.9 GHz), the US (5.9 GHz), and Japan (700 MHz)

- IEEE DSRC/WAVE, ETSI ITS G5, ARIB T109
  - Both build upon IEEE 802.11p

- Situation awareness as major year-one-application
  - ETSI DCC (Decentralized Congestion Control)

- **But many fundamental research questions still unanswered**
  - **Scalability, real-time capabilities, use of heterogeneous networks**

- Dagstuhl seminar series identified key challenges
  - Falko Dressler, Hannes Hartenstein, Onur Altintas and Ozan K. Tonguz, "Inter-Vehicle Communication - Quo Vadis," IEEE Communications Magazine, vol. 52 (6), pp. 170-177, June 2014.

Towards the Tactile Internet

Towards 5G
Huge Data Rates

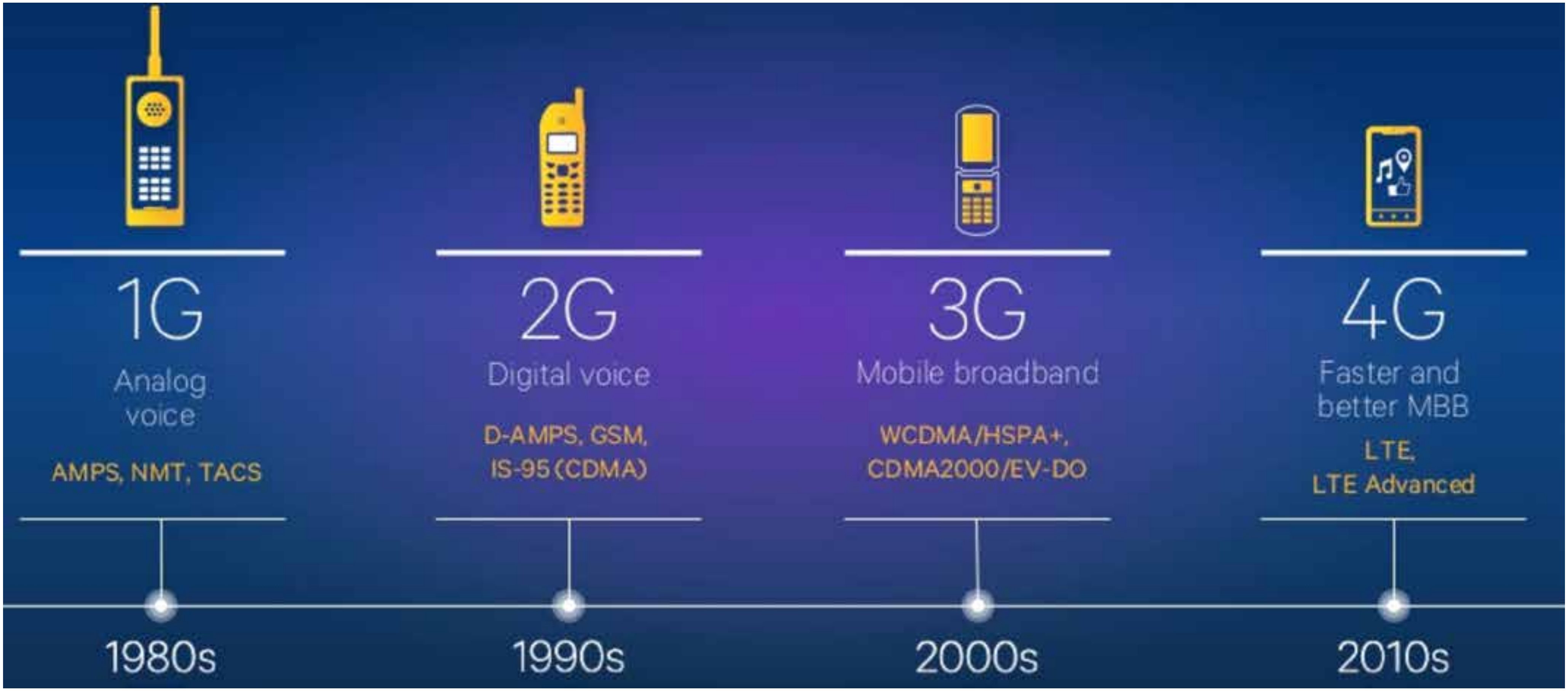
- Via Della Conciliazione

2005/4/4

2013/3/12

Source: http://www.spiegel.de/panorama/bild-889031-473266.html and http://www.spiegel.de/panorama/bild-889031-473242.html

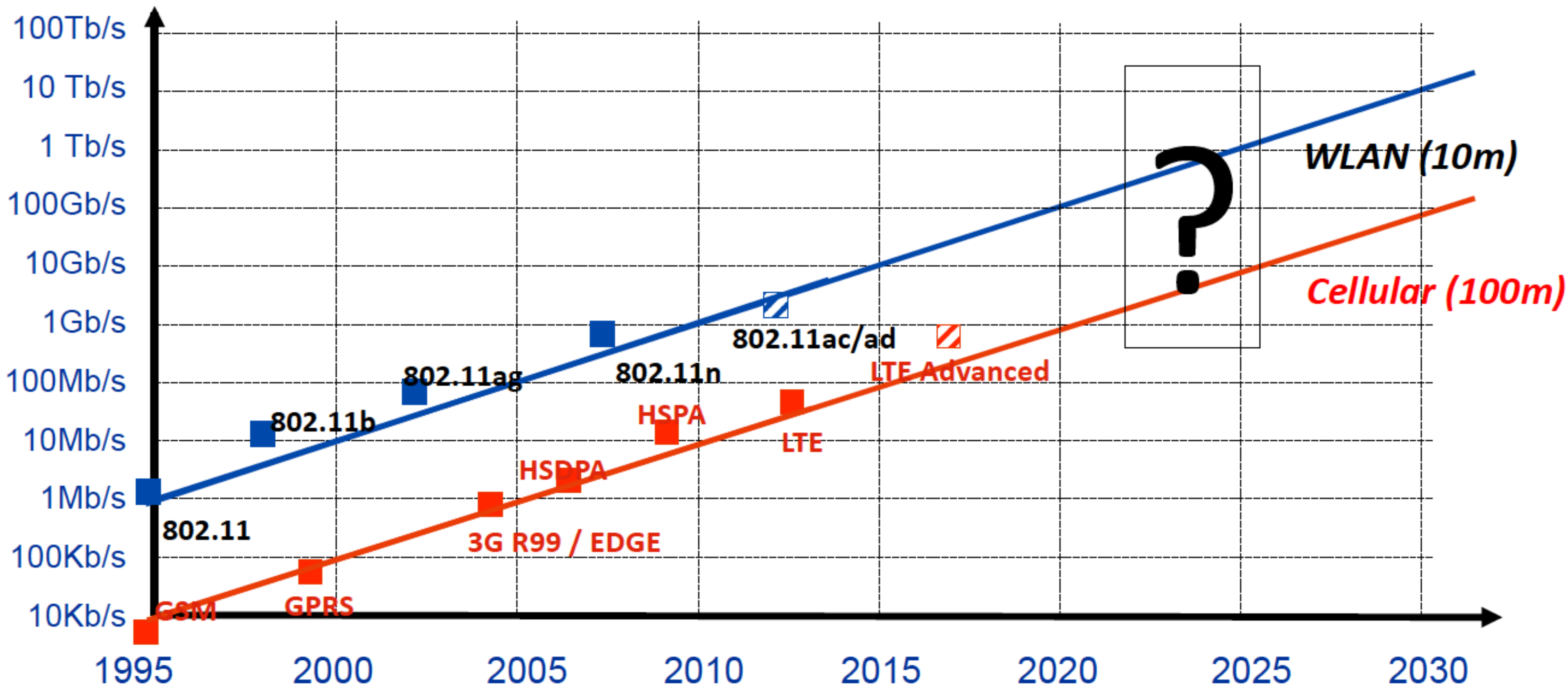
Towards 5G
The evolution…



Source: http://de.slideshare.net/qualcommwirelessevolution/qualcomm-5g-vision-presentation

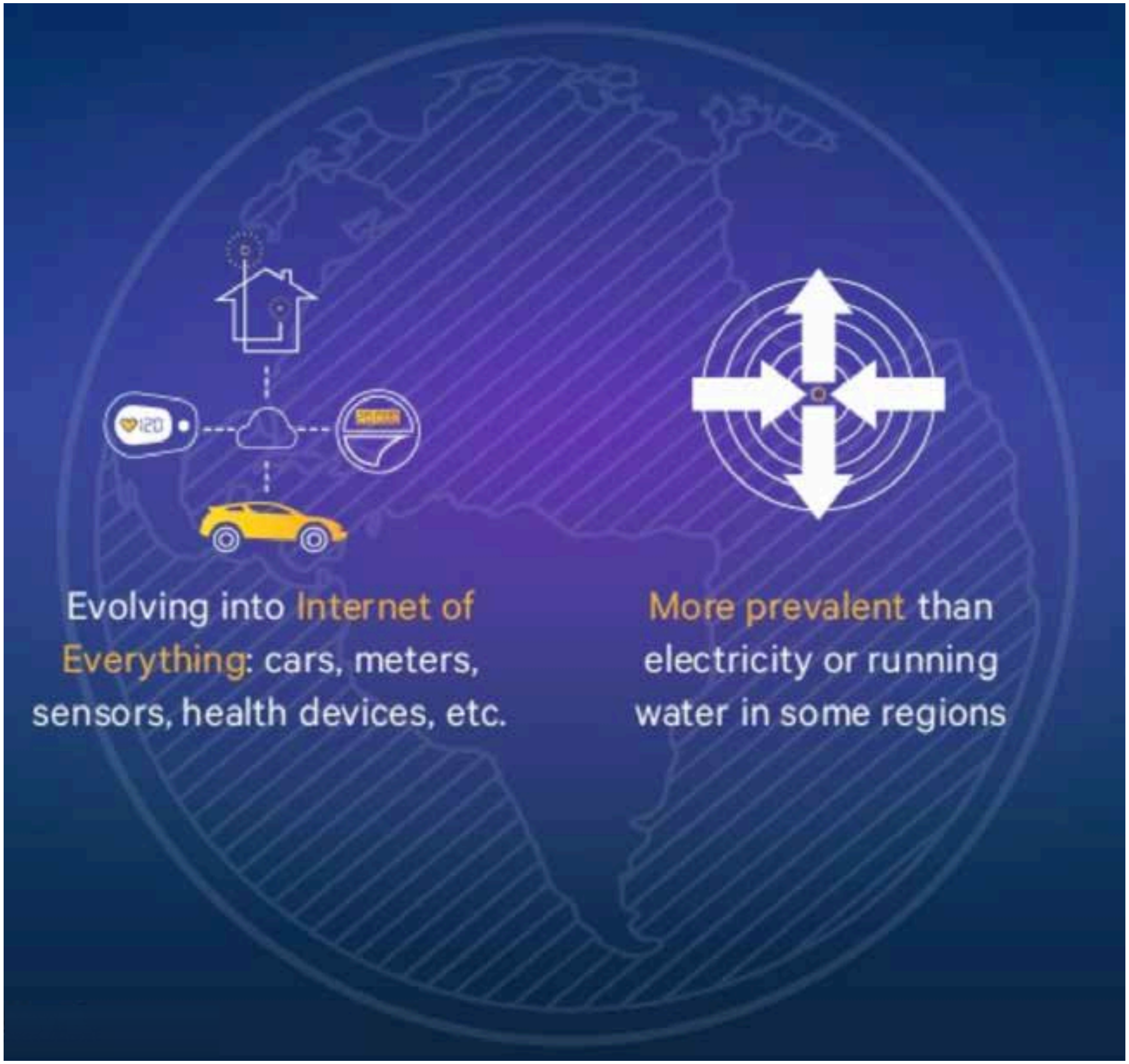
Towards 5G
Huge Data Rates

- 7 billion devices in 2014 → 500 billion devices in 2022



G. Fettweis, "5G: And Its Impact on Electronics", 5G Lab Germany

Towards 5G
The Internet of everything



Towards 5G
The evolution…

Source: http://de.slideshare.net/qualcommwirelessevolution/qualcomm-5g-vision-presentation

The New Challenge:
Delays in the Order of a Millisecond

Towards 5G and the Tactile Internet

Haptics and remote control as a game changer

Source: http://ostsee-spezial.de/?p=148

Towards 5G and the Tactile Internet

Latencies in the low milliseconds

- 10 cameras @ 100Hz frame rate → 100Gb/s Latency @ <10ms

Source: http://baumgartnerfl.lima-city.de/stadion.html

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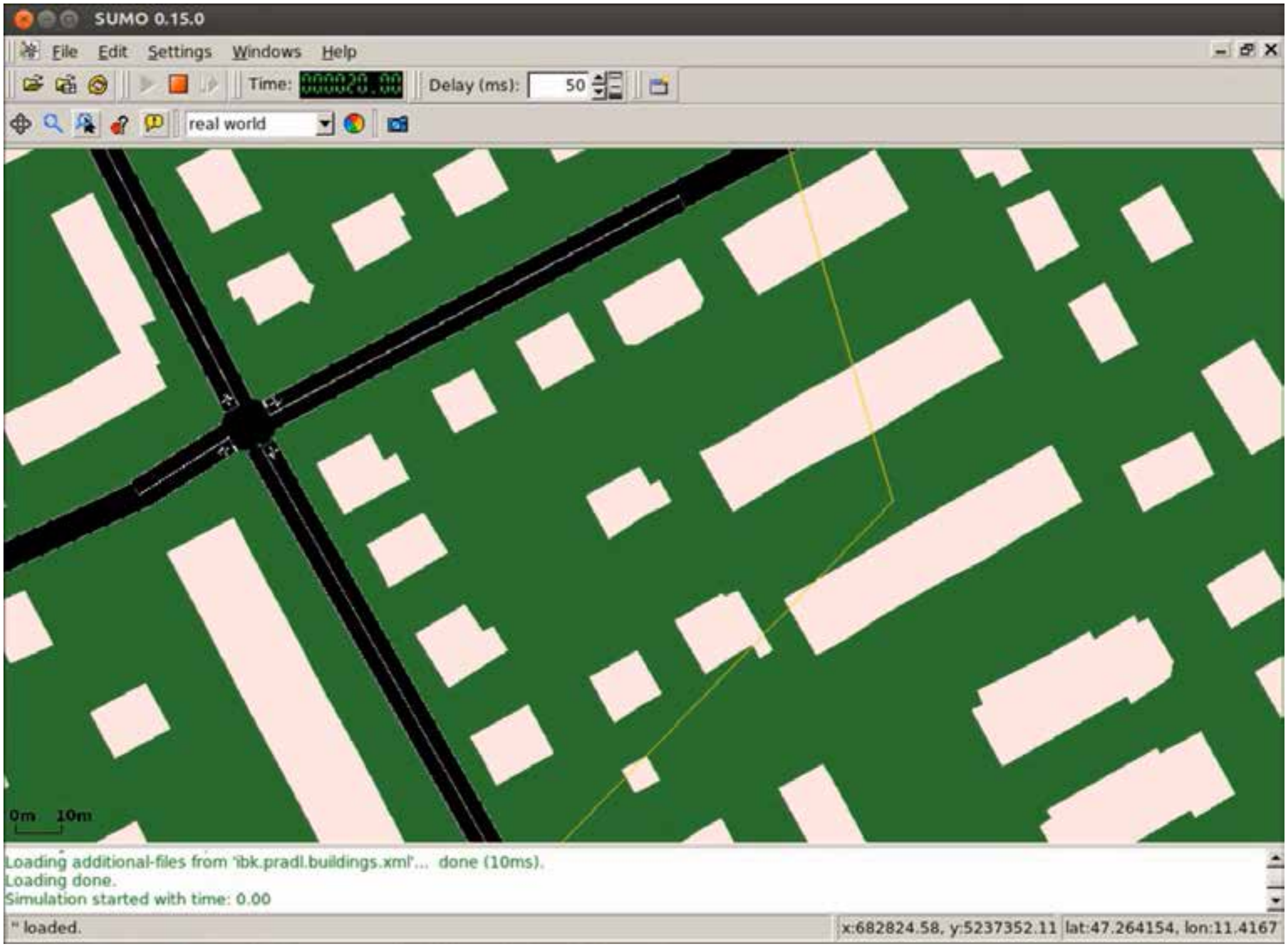
Towards 5G and the Tactile Internet
Distributed Real-Time Control Systems



Towards 5G and the Tactile Internet

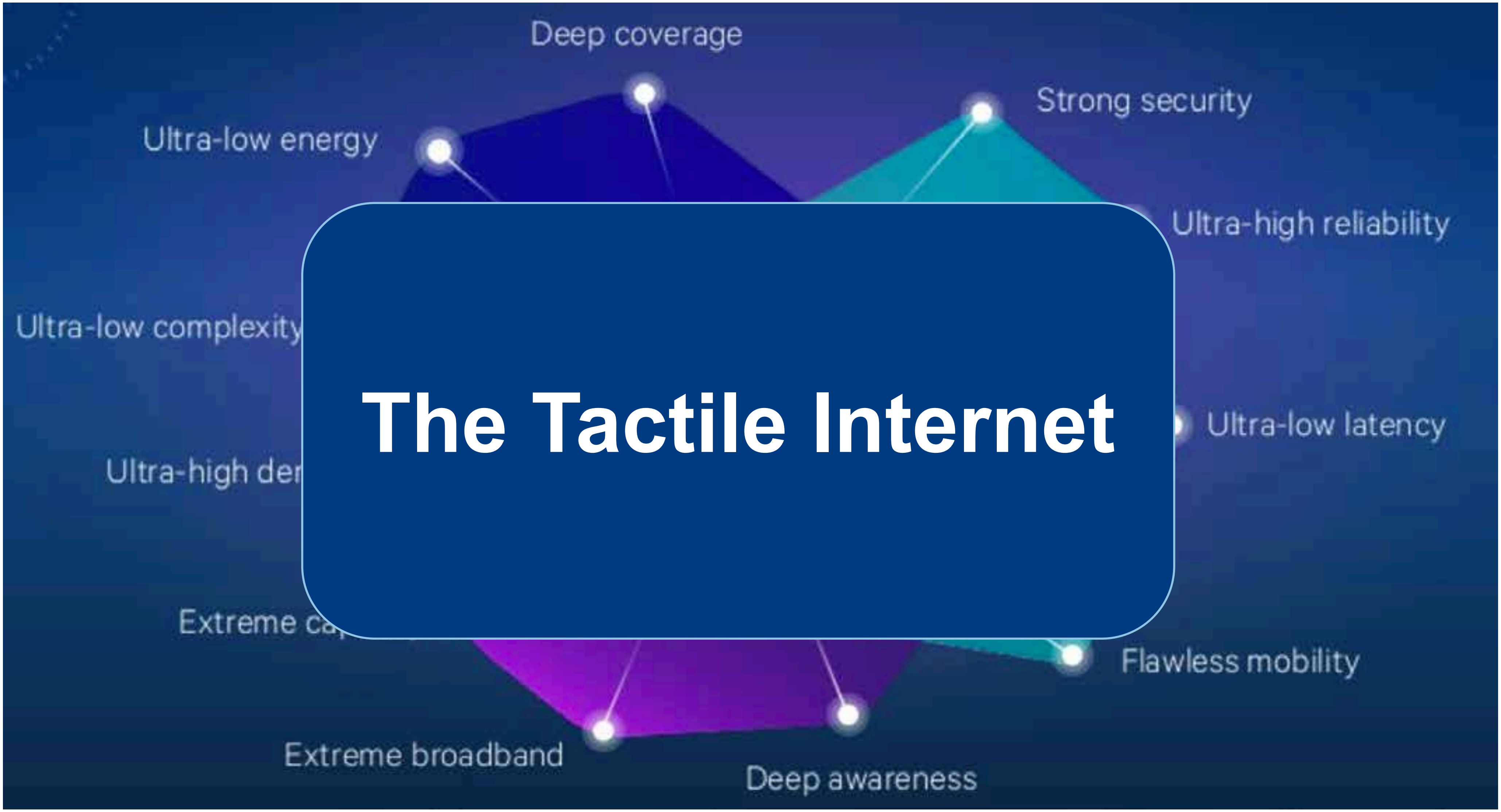
Networked Control

4G:
Content and communications

5G:
Networked Control

Towards 5G and the Tactile Internet

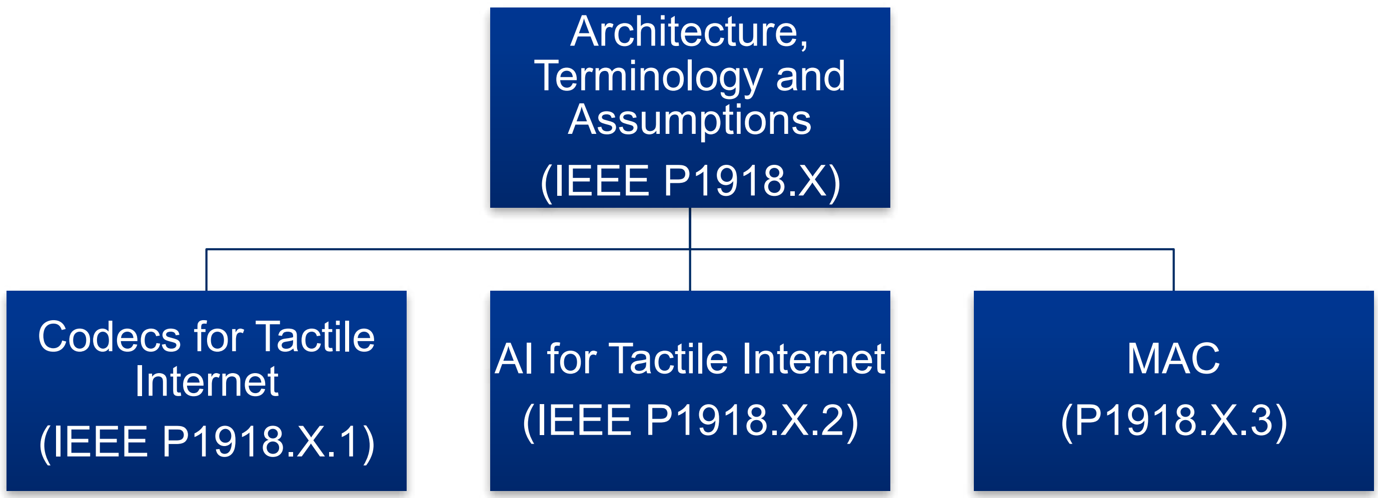
New Challenges



The Tactile Internet

Towards 5G and the Tactile Internet
Standardization

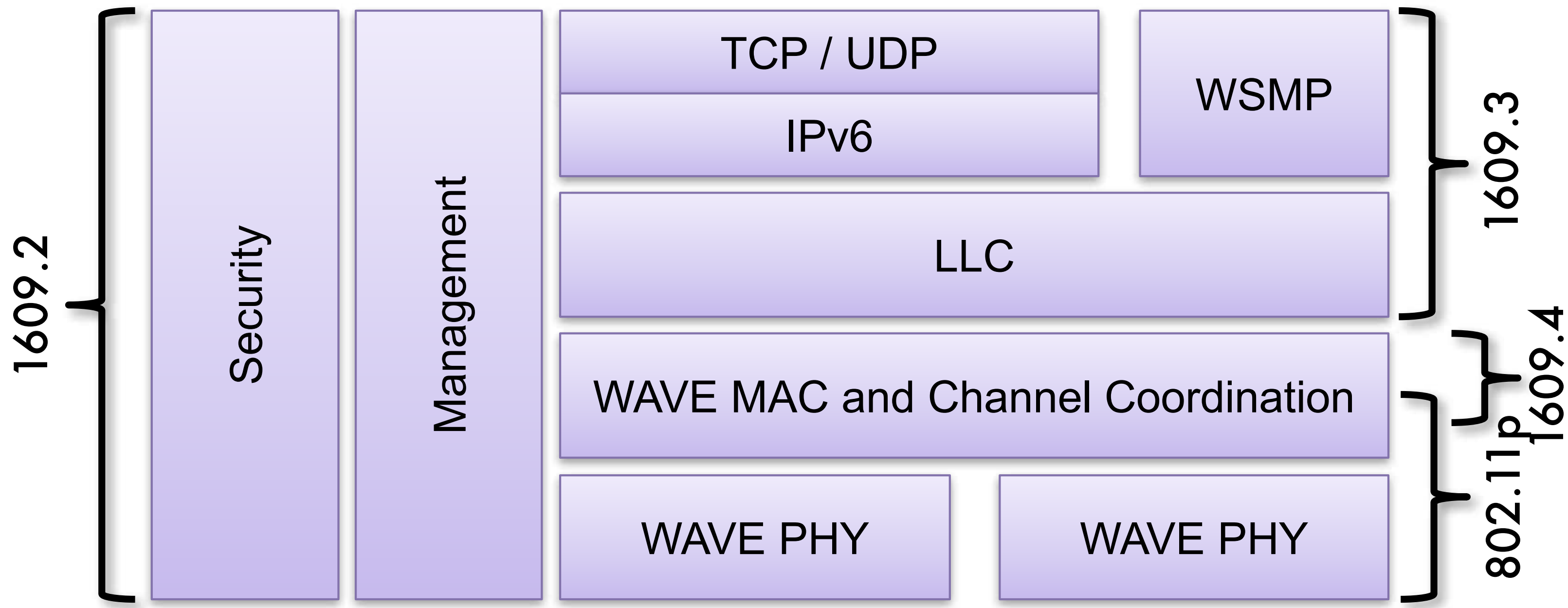
- IEEE COMSOC Subcommittee “Tactile Internet”
  - Involved in a new standards family P1918.X



Vehicular Networking

IVC Specific Protocols: DSRC/WAVE

- WAVE
  - IEEE 1609.1: “Core System”
  - IEEE 1609.2: Security
  - IEEE 1609.3: Network Services
  - IEEE 1609.4: Channel Management

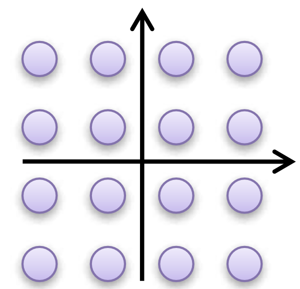


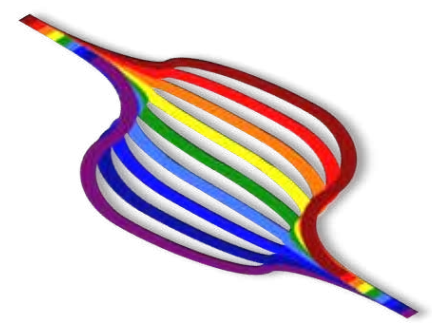
[1] Jiang, D. and Delgrossi, L., "IEEE 802.11p: Towards an international standard for wireless access in vehicular environments," Proceedings of 67th IEEE Vehicular Technology Conference (VTC2008-Spring), Marina Bay, Singapore, May 2008

[2] Uzcátegui, Roberto A. and Acosta-Marum, Guillermo, "WAVE: A Tutorial," IEEE Communications Magazine, vol. 47 (5), pp. 126-133, May 2009

IEEE 802.11p

- PHY layer almost identical to IEEE 802.11a
  - OFDM using 16 QAM
  - Reduced inter symbol interference (multipath effects and Doppler shift)
    - Doubled timing parameters
    - Channel bandwidth (10 MHz instead of 20 MHz)
    - Reduced throughput (3 ... 27 Mbit/s instead of 6 ... 54 Mbit/s)
    - Communication range of up to 1000 m
    - Vehicles’ velocity up to 200 km/h

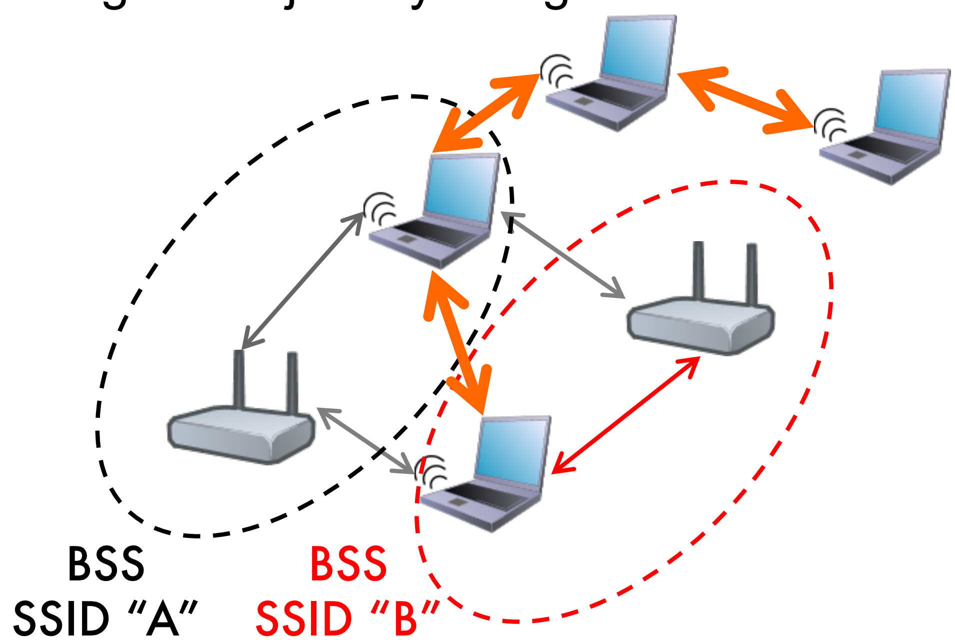




- MAC layer with extensions to IEEE 802.11a
  - Randomized MAC address
  - QoS (Priorities, see IEEE 802.11e, ...)
  - Support for multi channel and multi radio
  - New ad hoc mode

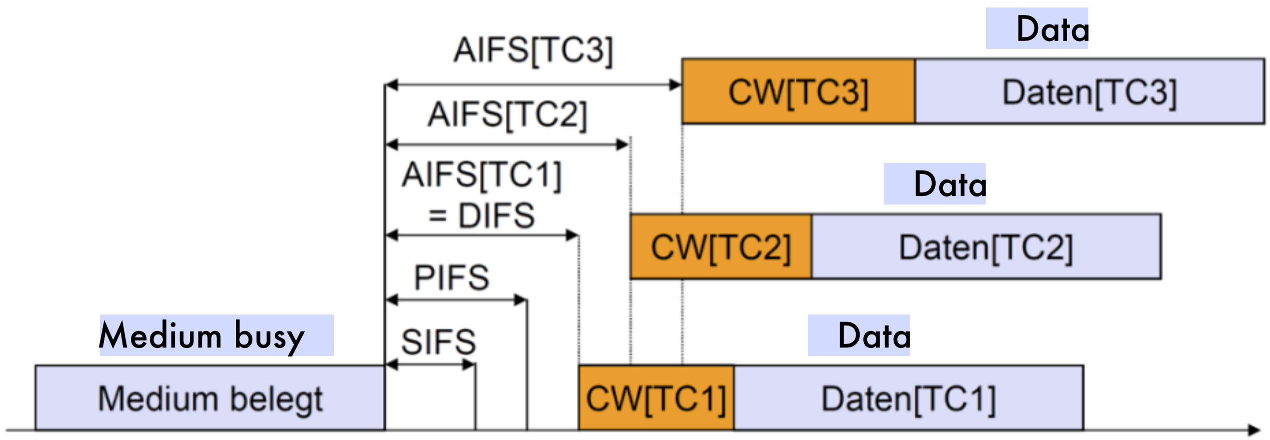
IEEE 802.11 Basic Service Set (BSS)

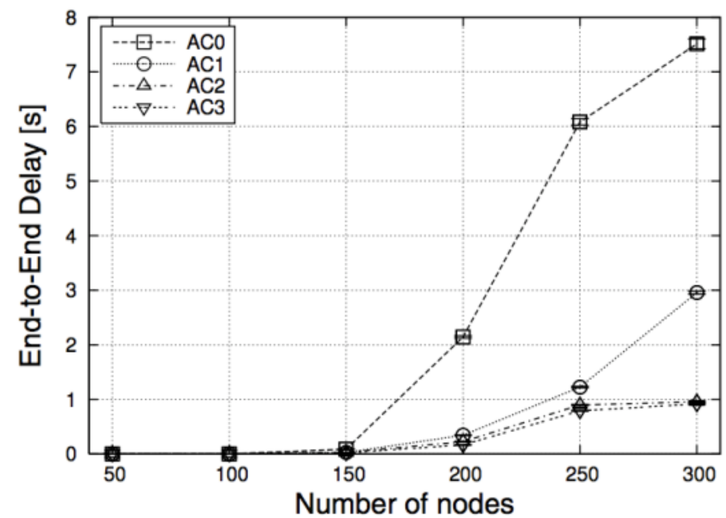
- New: 802.11 WAVE mode, now called OCB mode
  - Main mode for all WAVE nodes
  - Suggests the use of “Wildcard-BSS” in transmitted packets
  - Every node is required to receive all packets using a wildcard BSS
  - Inherently allows simultaneous transmission from and to a BSS
  - Membership management just by using a BSS



Access Control and QoS in WAVE

- Use of EDCA equivalent to IEEE 802.11e EDCA
- DCF -> EDCA (Enhanced Distributed Channel Access)
- Definition of four Access Categories (AC)
  - AC0 (lowest) to AC3 (highest priority)
- Introduction of AIFS (Arbitration Inter-Frame Space)





- ACs define...
  - CWmin, CWmax, AIFS, TXOP-Limit (max. continuous channel use)
- Management data are transmitted using DIFS instead of an AIFS

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Channel Management

- WAVE uses a dedicated frequency range in the 5.9 GHz band
  - Exclusive for V2V and V2I communication
  - Strictly regulated but no license costs
  - In the US, FCC reserved 7 channels a 10 MHz ("U.S. DSRC")

…	Critical Safety of Life ch 172 5.860GHz	SCH ch 174 5.870GHz	SCH ch 176 5.880GHz	Control Channel (CCH) ch 178 5.890GHz	SCH ch 180 5.900GHz	SCH ch 182 5.910GHz	Hi-Power Public Safety ch 184 5.920GHz	…

    - 1 control and 4 service channels to be used by applications

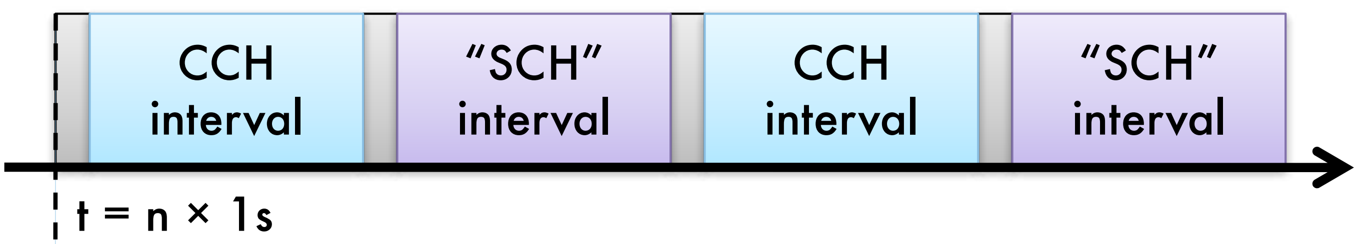
  - In Europa, ETSI reserved 5 channels a 10 MHz

SCH ch 172 5.860GHz	SCH ch 174 5.870GHz	SCH ch 176 5.880GHz	SCH ch 178 5.890GHz	CCH ch 180 5.900GHz

[1] ETSI ES 202 663 V1.1.0 (2010-01) : Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band

Channel Management

- Channel Management
  - Management and safety information on the Control Channel (CCH)
    → single radios have to switch to the CCH at known times
  - Two-way communication on the Service Channel (SCH)
- Slot management
  - Synchronization using GPS
  - Standard: 100ms sync interval including 50ms on the CCH
  - Slots start with a guard interval



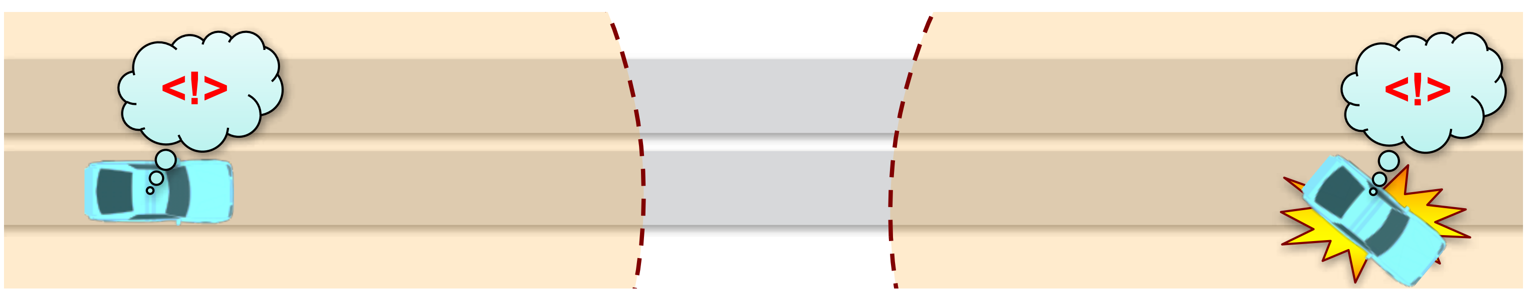
[1] IEEE Vehicular Technology Society, "IEEE 1609.4 (Multi-channel Operation)," IEEE Std, November, 2006

Beaconing and Vehicular Ad Hoc Networks

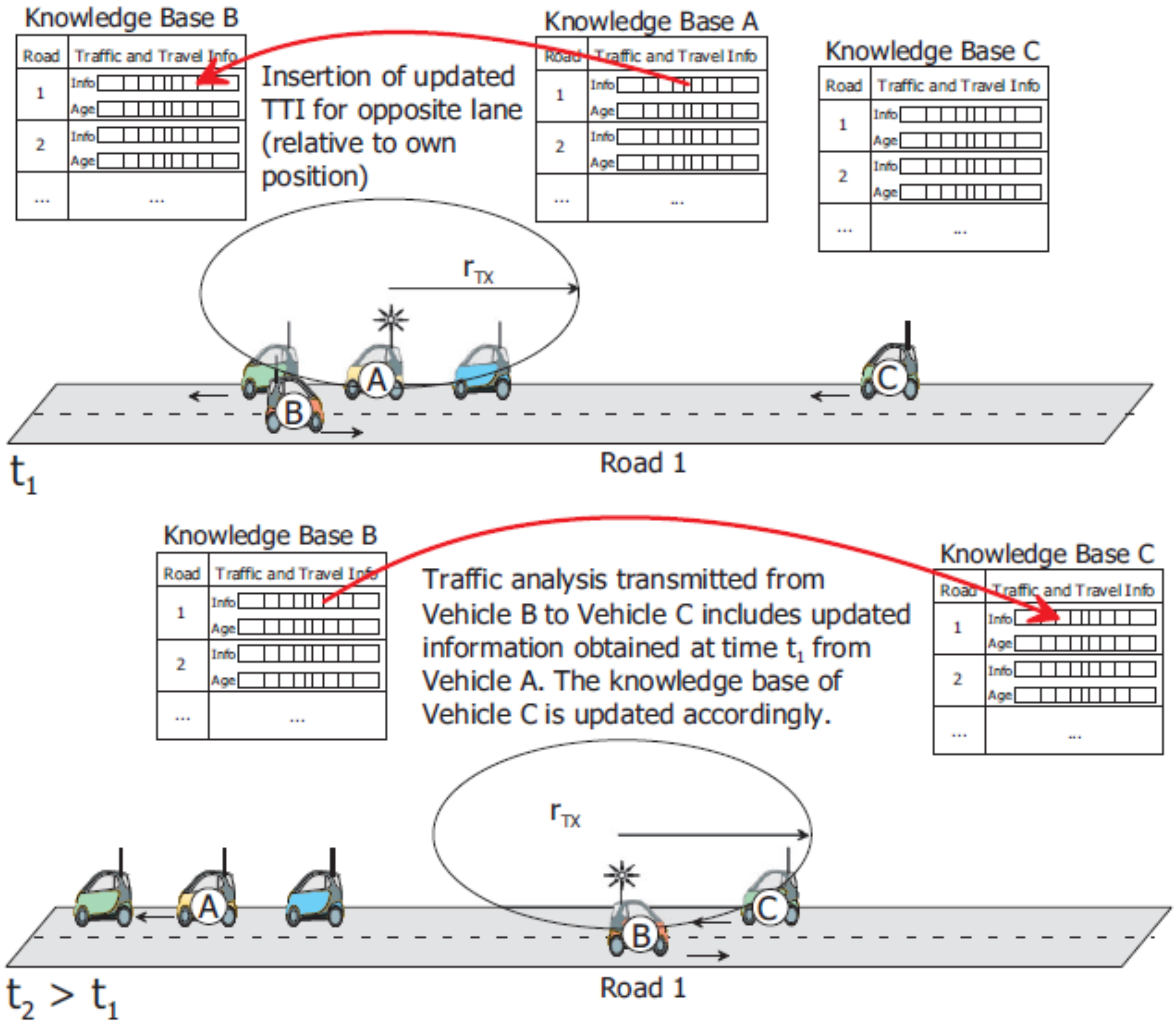
The SOTIS Approach

- Fully distributed approach
  - No communication infrastructure needed
  - No data loss in fragmented networks
  - No unique node identifiers mandated
  - No network topology assumed, created, or maintained

- SOTIS: local knowledge bases + beaconing
  - Aggregate all sensed data + received data
  - Periodic broadcast of entries (beaconing)
    - Ex.: one beacon every five seconds
  - No congestion control in the wireless network

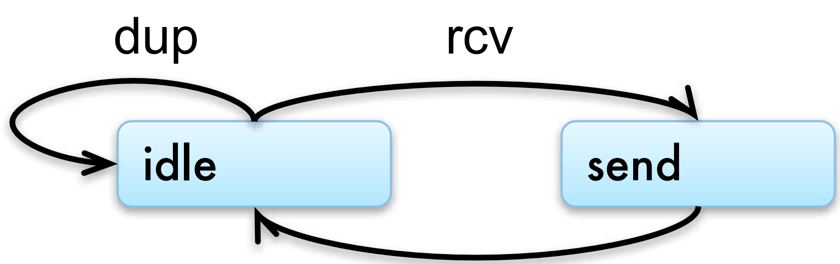


SOTIS

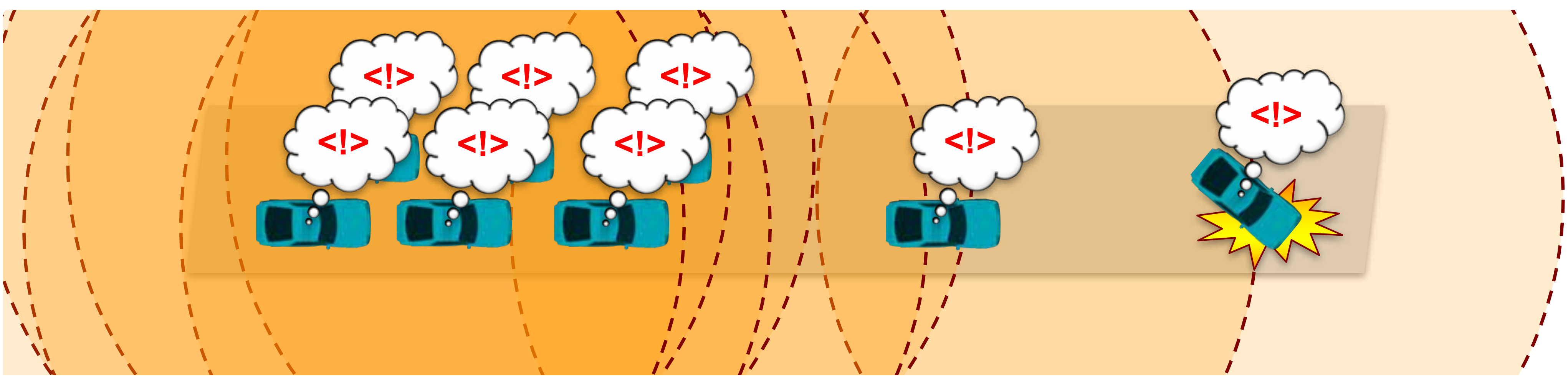

Knowledge Base B
Road
Traffic and Travel Info
Info
Age
Knowledge Base A
Knowledge Base C
Insertion of updated TTI for opposite lane (relative to own position)
r_TX
A
B
C
t_1
Road 1
Traffic analysis transmitted from Vehicle B to Vehicle C includes updated information obtained at time t_1 from Vehicle A. The knowledge base of Vehicle C is updated accordingly.
t_2 > t_1

Broadcast Storm Problem

- Flooding (Multi-Hop Broadcast)
  - Simplest protocol: „Smart Flooding“:



  - Problem: Broadcast Storm
    - Superfluous re-broadcasts overload channel



Broadcast Suppression

- Estimate distance to sender as $0 \leq \rho_{ij} \leq 1$

- GPS based

$$\varrho_{ij} = \begin{cases} 0 & \text{if } D_{ij} < 0 \\ \frac{D_{ij}}{R} & \text{if } 0 \leq D_{ij} < R \text{ (approx. transmission radius)} \\ 1 & \text{otherwise} \end{cases}$$

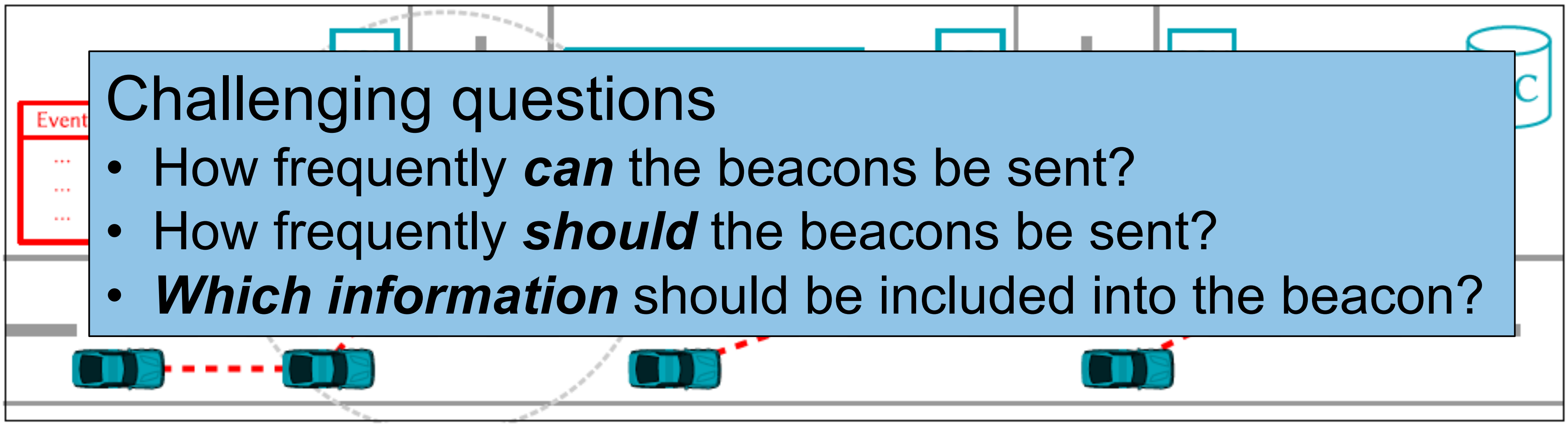
- RSS based

$$\varrho_{ij} = \begin{cases} 0 & \text{if } RSS_x < RSS_{min} \\ \frac{RSS_{max} - RSS_x}{RSS_{max} - RSS_{min}} & \text{if } RSS_{min} \leq RSS_x < RSS_{max} \\ 1 & \text{otherwise} \end{cases}$$

[1] Wisitpongphan, Nawaporn and Tonguz, Ozan K. and Parikh, J. S. and Mudalige, Priyantha and Bai, Fan and Sadekar, Varsha, "Broadcast Storm Mitigation Techniques in Vehicular Ad Hoc Networks," IEEE Wireless Communications, vol. 14 (6), pp. 84-94, December 2007

Fully Distributed: Adaptive Traffic Beacon (ATB)

- **Beacon interval:** measure of channel quality and message priorities
- **Infrastructure elements:** RSUs of different capabilities can be included
  - Lightweight SSUs (service support unit)
  - Interconnected RSUs



Challenging questions

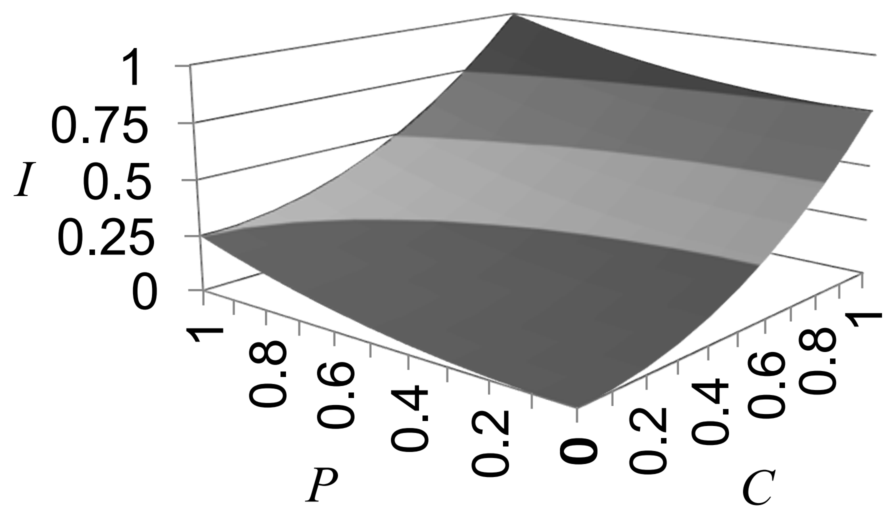
- How frequently ***can*** the beacons be sent?
- How frequently ***should*** the beacons be sent?
- ***Which information*** should be included into the beacon?

[1] Christoph Sommer, Ozan K. Tonguz and Falko Dressler, "Traffic Information Systems: Efficient Message Dissemination via Adaptive Beaconing," IEEE Communications Magazine, vol. 49 (5), pp. 173-179, May 2011

[2] Christoph Sommer, Ozan K. Tonguz and Falko Dressler, "Adaptive Beaconing for Delay-Sensitive and Congestion-Aware Traffic Information Systems," Proceedings of 2nd IEEE Vehicular Networking Conference (VNC 2010), Jersey City, NJ, December 2010, pp. 1-8

Adaptive Traffic Beacon (ATB)

- Adaptive selection of beacon interval ΔI
  - Consider message utility P
  - Consider channel quality C
- Choose interval from range I_{min} to I_{max}
  - Use factor w_I to increase weight of C (ex. w_I=0.75)
  - $\Delta I = ((1 - w_I) \times P^2 + (w_I \times C^2)) \times (I_{\text{max}} - I_{\text{min}}) + I_{\text{min}}$



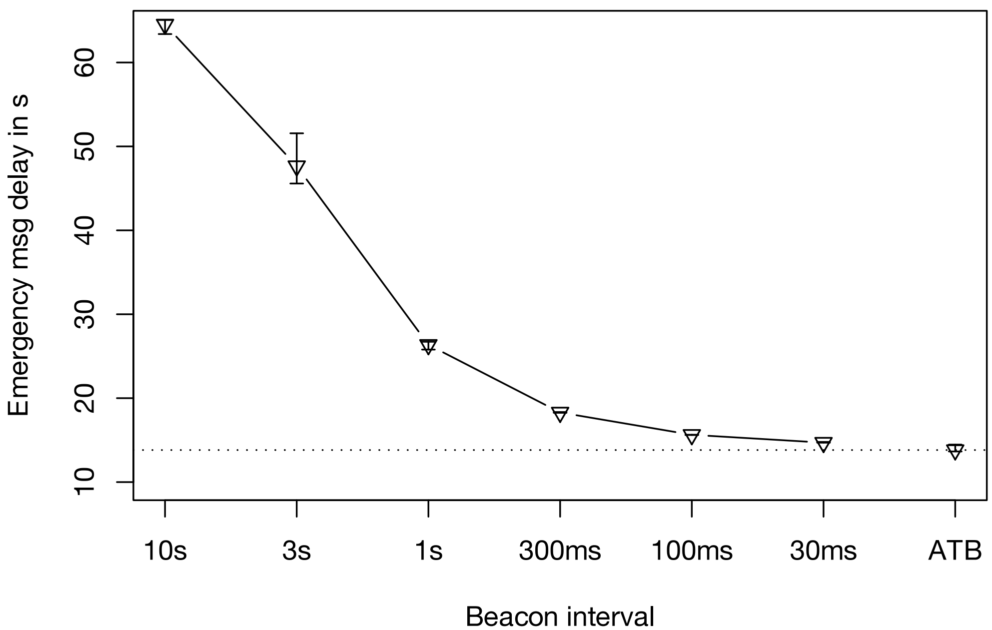
Adaptive Traffic Beacon (ATB)

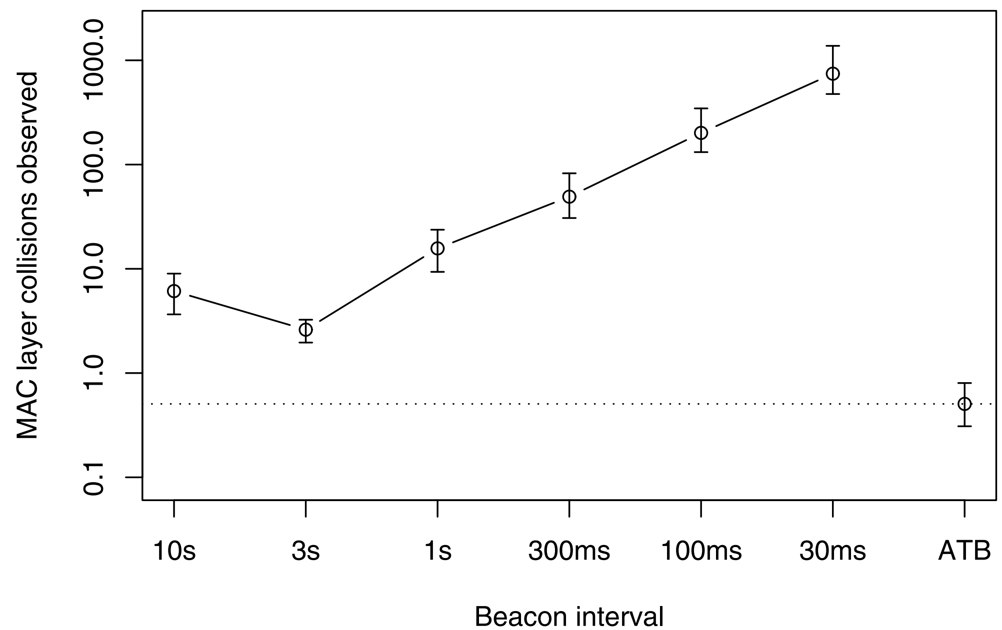
- Adaptive selection of beacon interval ΔI
  - Calculation of message utility P based on metrics of (ex.)
    - A: age of information
    - D_e: distance to source of information
    - D_r: distance to closest Road Side Unit (RSU)
    - B: ratio of beacon contents received from Road Side Unit (RSU)
  - Calculation of channel quality C based on metrics of (ex.)
    - N: (estimated) number of neighbors (→ *future*)
    - S: (observed) signal-to-noise ratio (→ *present*)
    - K: (measured) collisions on channel (→ *past*)

$$P = \frac{A + D_e + D_r}{3} \times B \qquad C = \frac{N + w_C (S + K)/2}{1 + w_C}$$

State of the Art: Adaptive Beaconing

- First proposed in Adaptive Traffic Beacon (ATB) protocol

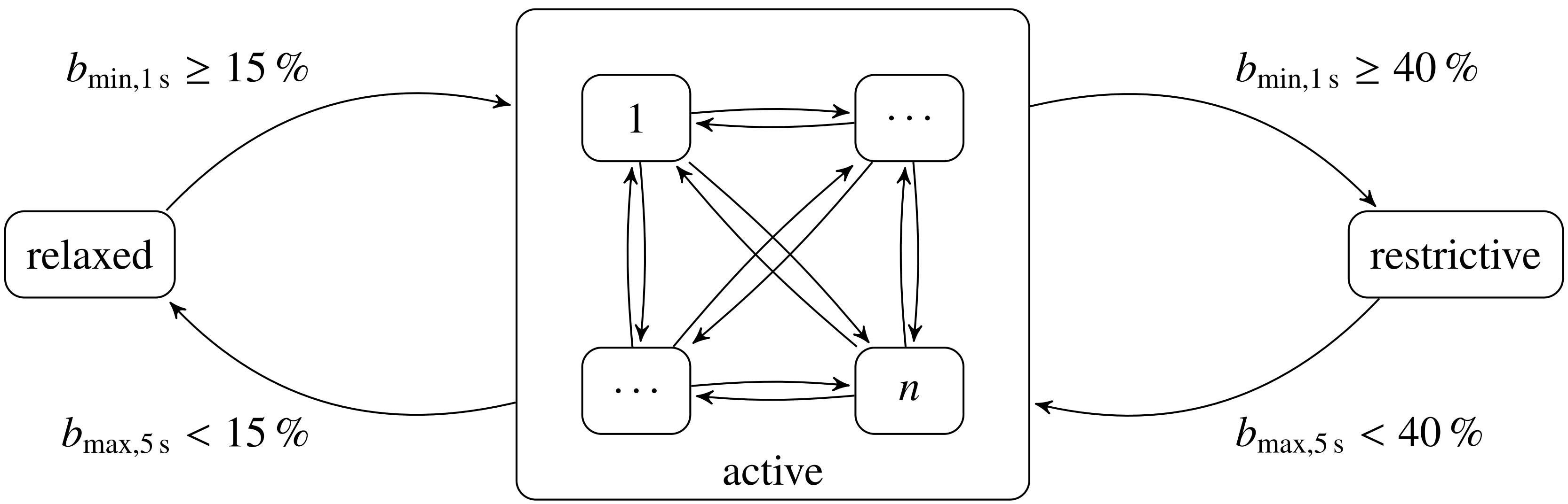




[1] Christoph Sommer, Ozan K. Tonguz and Falko Dressler, "Traffic Information Systems: Efficient Message Dissemination via Adaptive Beaconing," *IEEE Communications Magazine*, vol. 49 (5), pp. 173-179, May 2011

State of the Art: Adaptive Beaconing

- Later introduced in standardization
  - ETSI ITS-G5 developed DCC (Decentralized Congestion Control) with TRC (Transmit Rate Control)
  - b_t is the “busy ratio” of the channel
  - Rather coarse grained measurement intervals

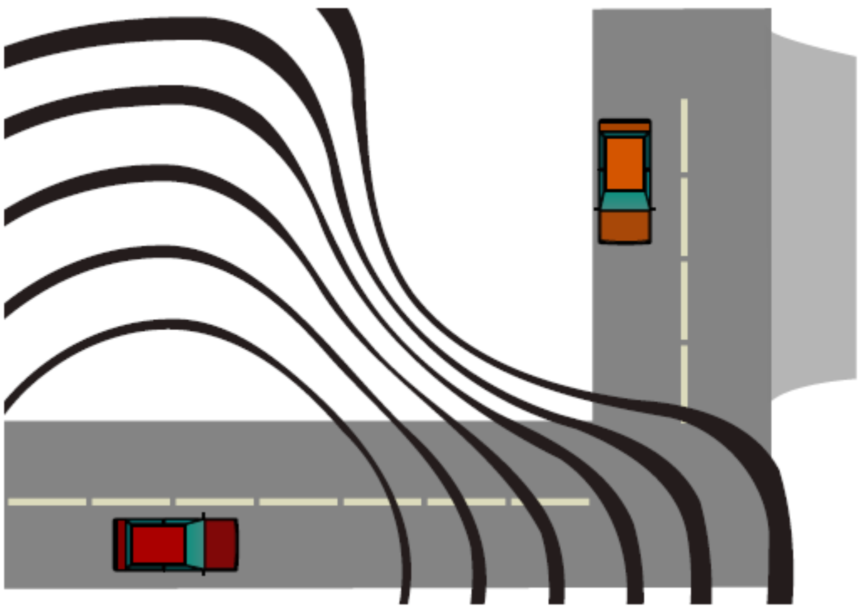


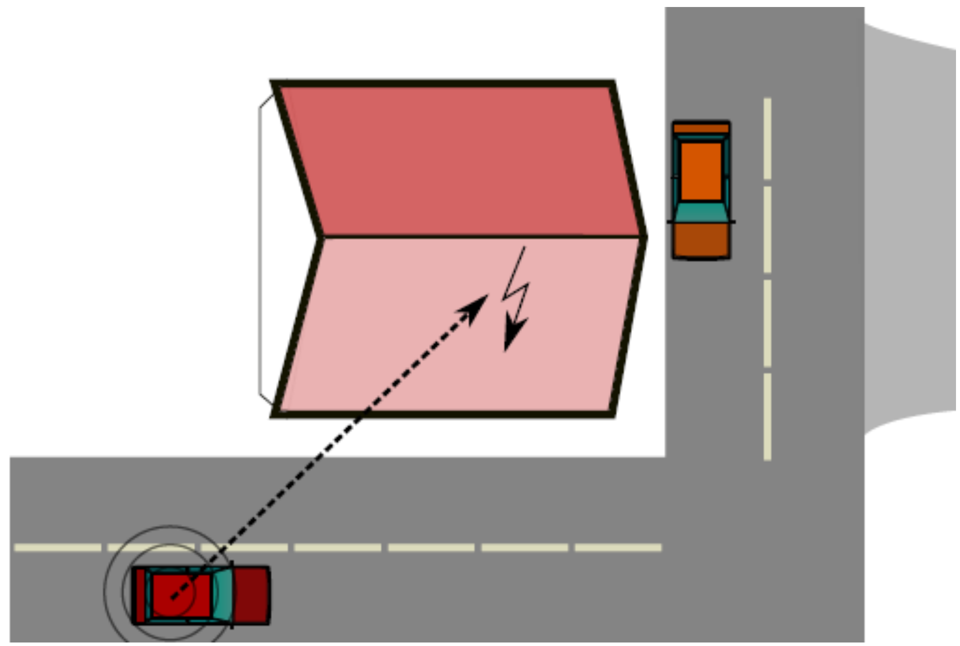
[1] Werner, Marc and Lupoaie, Radu and Subramanian, Sundar and Jose, Jubin, "MAC Layer Performance of ITS G5 - Optimized DCC and Advanced Transmitter Coordination," Proceedings of 4th ETSI TC ITS Workshop, Doha, Qatar, February 2012

Problem Solved?

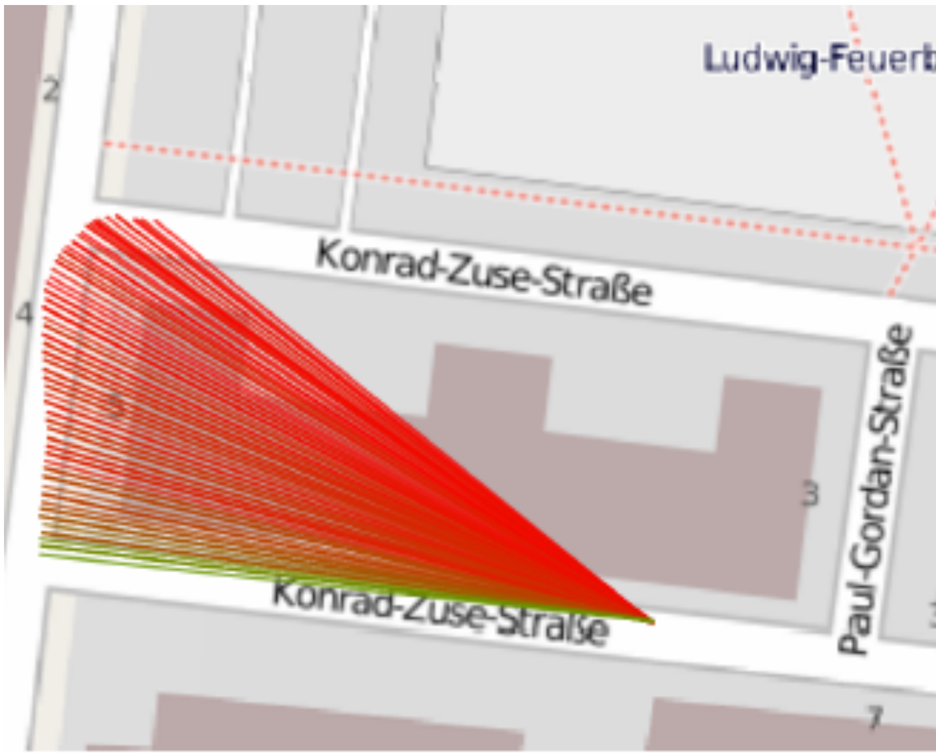
- Maybe we all overlooked some issues!

- Antenna characteristics
- Radio signal shadowing





Experimental Validation

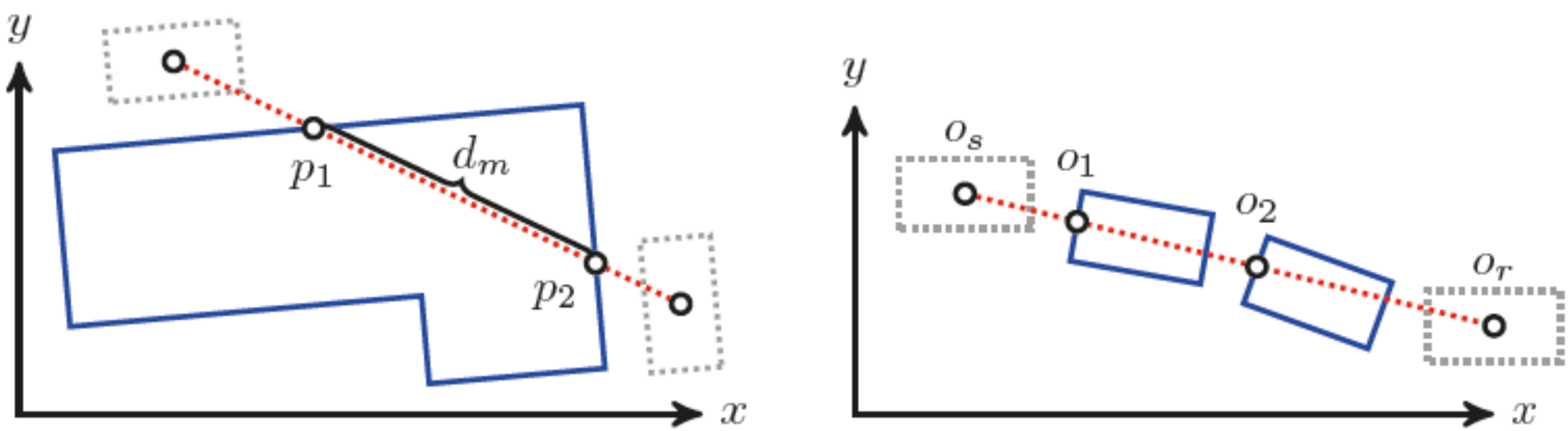


[1] Christoph Sommer, David Eckhoff, Reinhard German and Falko Dressler, "A Computationally Inexpensive Empirical Model of IEEE 802.11p Radio Shadowing in Urban Environments," Proceedings of 8th IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS 2011), Bardonecchia, Italy, January 2011, pp. 84-90

[2] David Eckhoff, Christoph Sommer, Reinhard German and Falko Dressler, "Cooperative Awareness At Low Vehicle Densities: How Parked Cars Can Help See Through Buildings," Proceedings of IEEE Global Telecommunications Conference (GLOBECOM 2011), Houston, TX, December 2011

Establishment of New Models

- Models allow taking into consideration
  (a) static and
  (b) moving obstacles
- **Research question: What is their impact on beaconing?**



(a) static obstacles (b) moving obstacles

Towards new Beaconing Concepts

- **DynB – Dynamic Beaconing**

- Considering all the radio shadowing effects to adapt very quickly to the current channel quality
- Main idea: continuously observe the load of the wireless channel to calculate the current beacon interval

- $I = I_{min} + r\ (I_{max} - I_{min})$

  with $I_{max} = (N+1)\ I_{min}$ (N is the number of neighbors)
  and $r = (b_t / b_{des}) - 1$ clipped in [0, 1]

[1] Christoph Sommer, Stefan Joerer, Michele Segata, Ozan K. Tonguz, Renato Lo Cigno and Falko Dressler, "How Shadowing Hurts Vehicular Communications and How Dynamic Beaconing Can Help," Proceedings of 32nd IEEE Conference on Computer Communications (INFOCOM 2013), Mini-Conference, Turin, Italy, April 2013

How Busy Can/Should the Channel Be?

- Assuming a payload of l = 512 bit (at 18 Mbit/s), we obtain

$$t_{busy} = T_{preamble} + T_{signal} + T_{sym} \lceil (16 + l + 6) / N_{DBPS} \rceil = 104\ \mu s$$

- Using a minimum AIFS and an average initial backoff counter, we get a maximum b_t

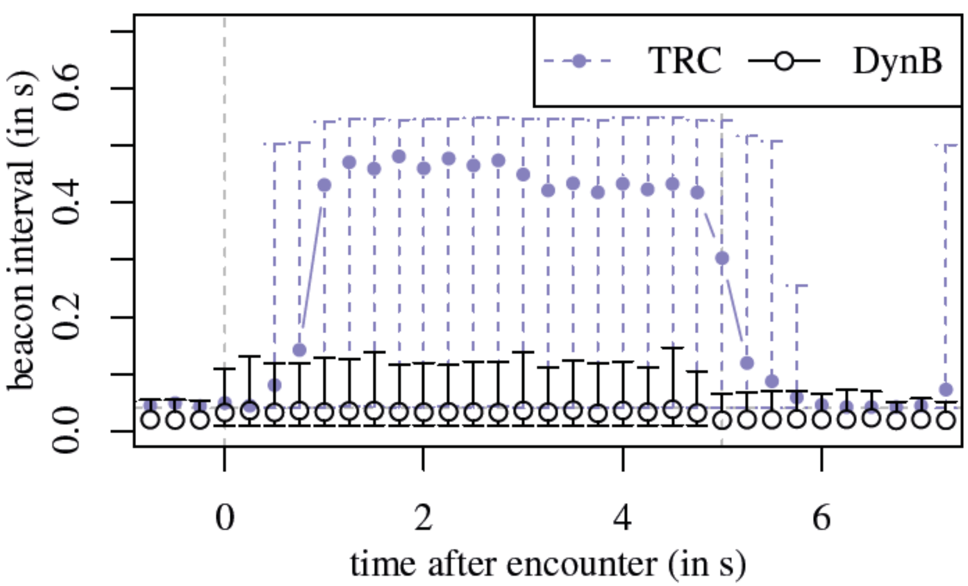
$$b_t = t_{busy} / (t_{busy} + t_{aifs} + t_{idle}) = 0.64$$

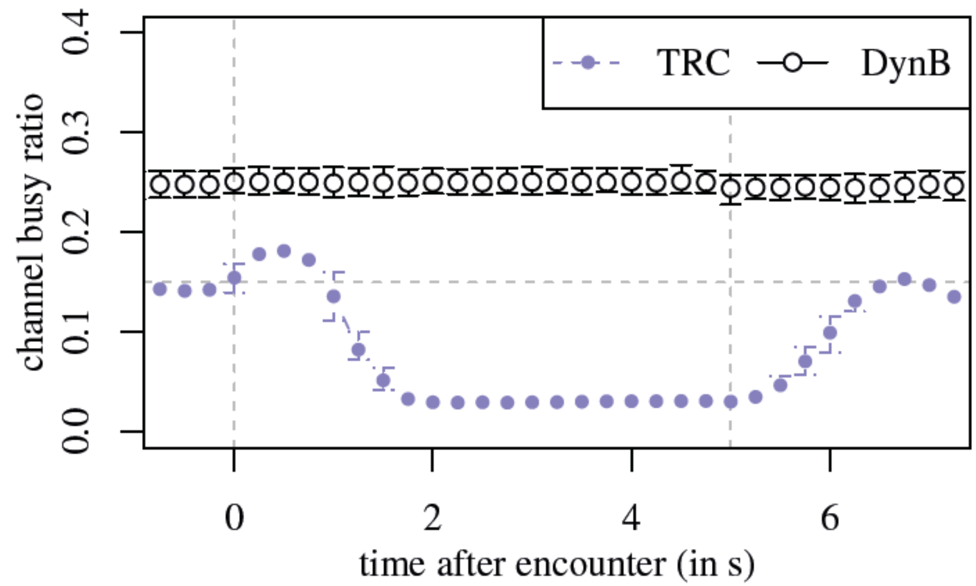
- With some maximum collision probability of 0.05, we get a maximum b_t

$$b_t = 0.25$$

Handling Dynamics in the Environment

- Assuming two larger clusters of vehicles meeting spontaneously (e.g., at intersections in suburban or when two big trucks leave the freeway)



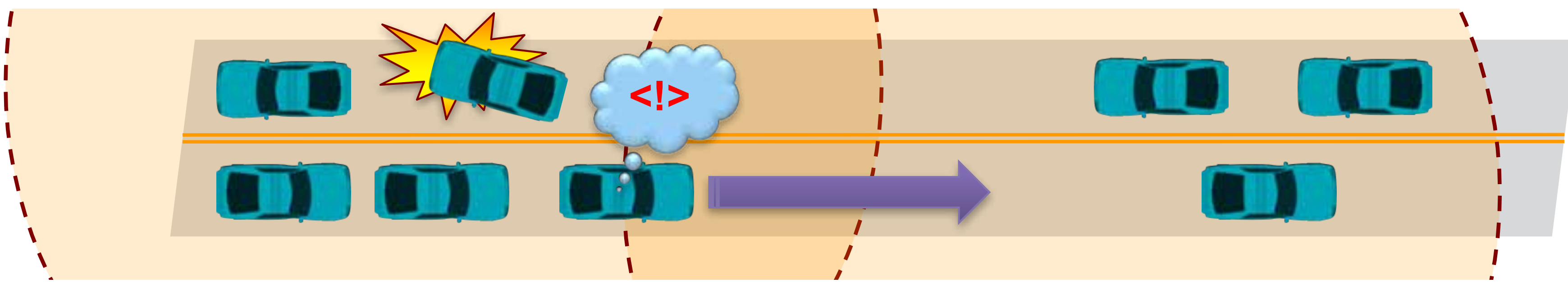


Remaining Problems

- Temporary network fragmentation

DV-CAST

- Idea: detect current scenario, switch between protocols
- Check for fragmented network
  - Network connected → perform broadcast suppression



DV-CAST

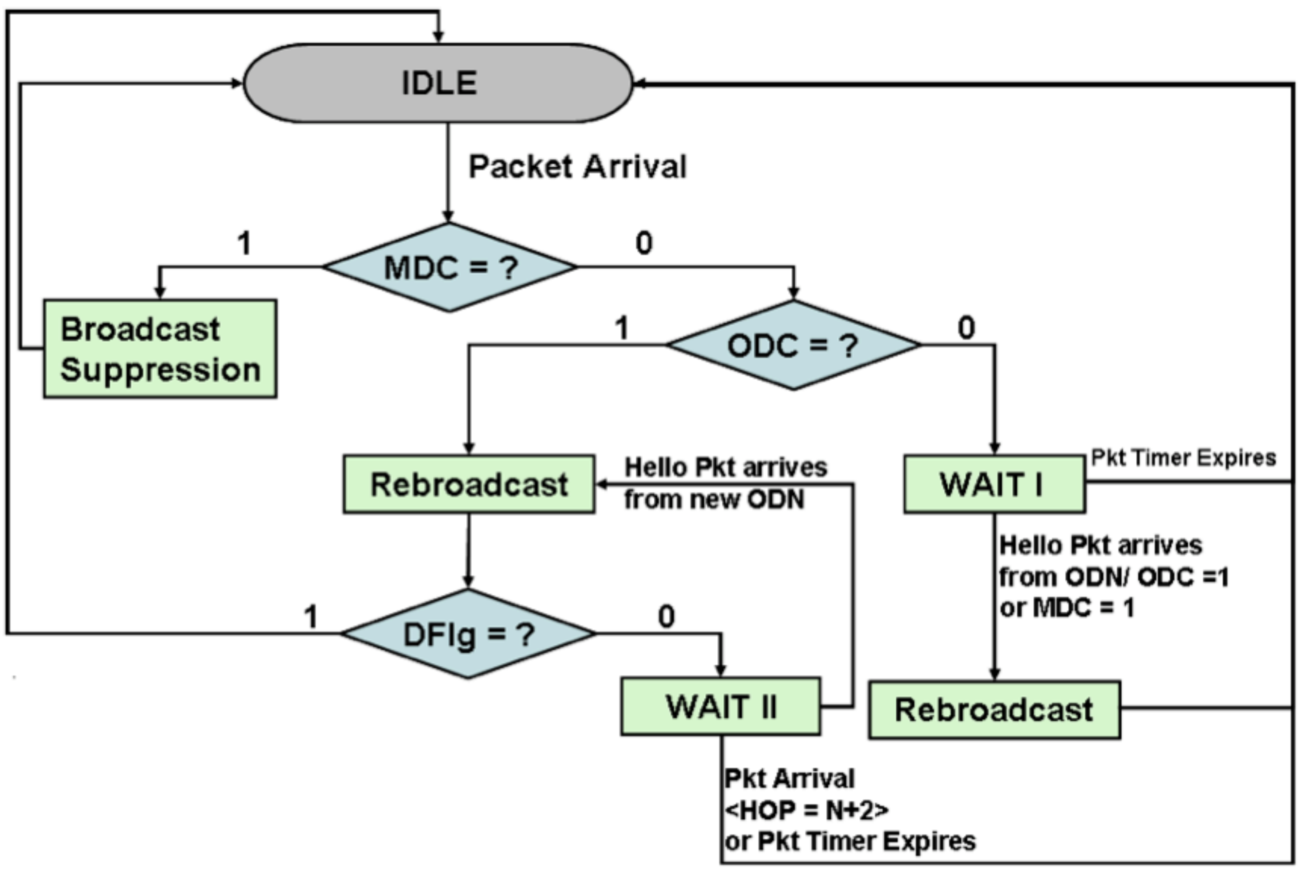
- Mechanism
  - Nodes periodically send Hello beacons containing position, speed
  - Nodes maintain 3 neighbor tables
    - Same direction, ahead
    - Same direction, driving behind
    - Opposite direction
  - Messages contain source position and Region of Interest (ROI)

  - For each message received, evaluate 3 Flags:
    - Destination Flag (DFlg):
      Vehicle in ROI, approaching source
    - Message Direction Connectivity (MDC):
      $\exists$ neighbor driving in same direction, further away from source
    - Opposite Direction Connectivity (ODC):
      $\exists$ neighbor driving in opposite direction

[1] Tonguz, Ozan K. and Wisitpongphan, N. and Bai, F., "DV-CAST: A distributed vehicular broadcast protocol for vehicular ad hoc networks," IEEE Wireless Communications, vol. 17 (2), pp. 47-57, April 2010

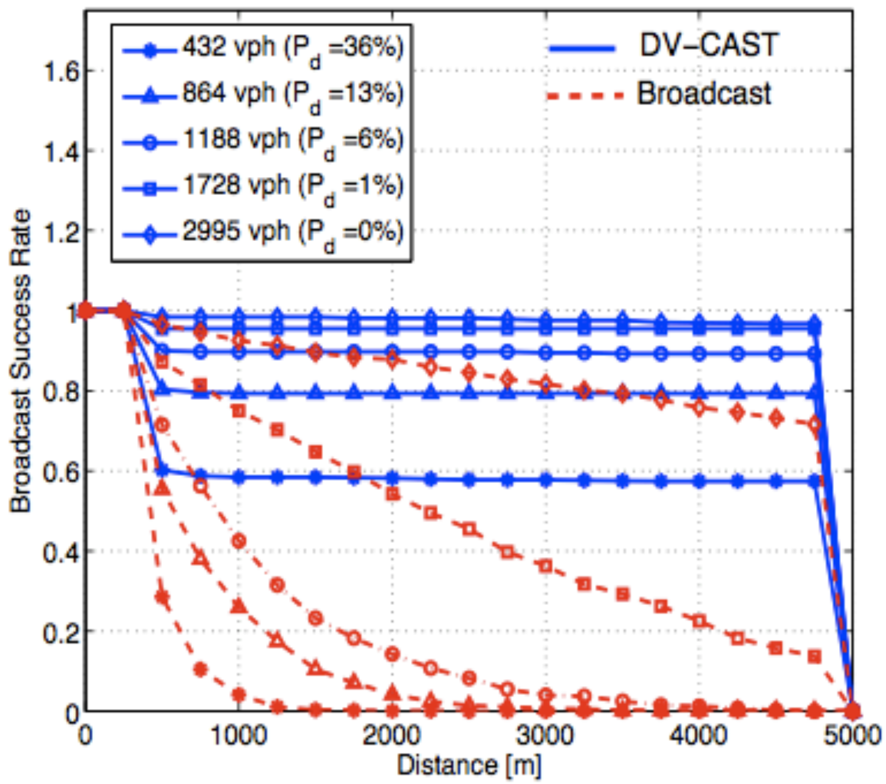
DV-CAST

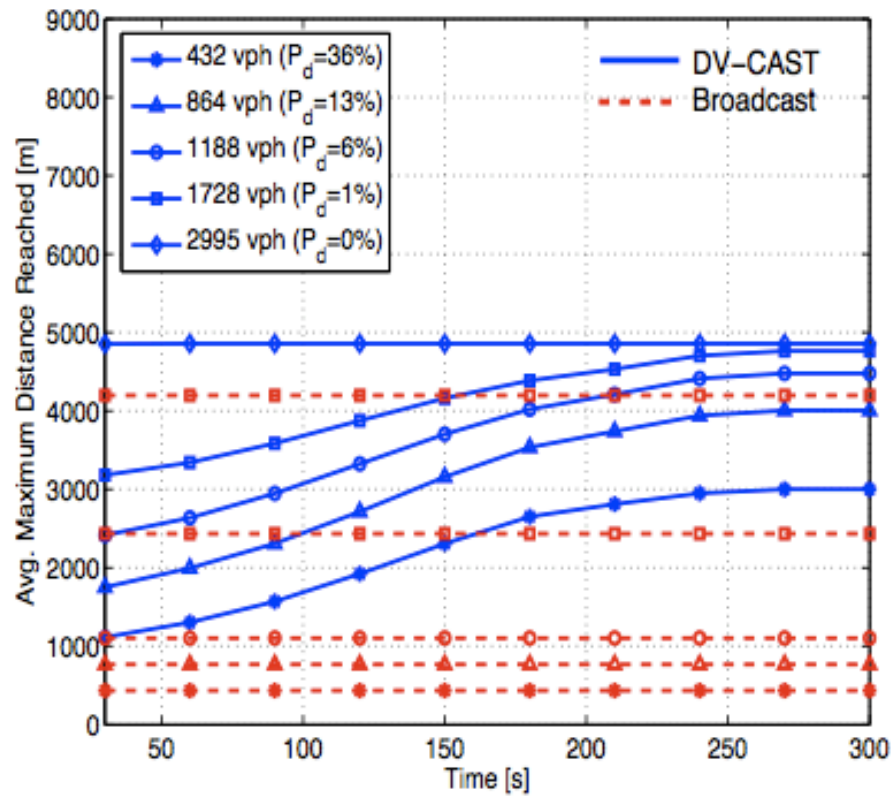
- Algorithm



DV-CAST

- Simulation results

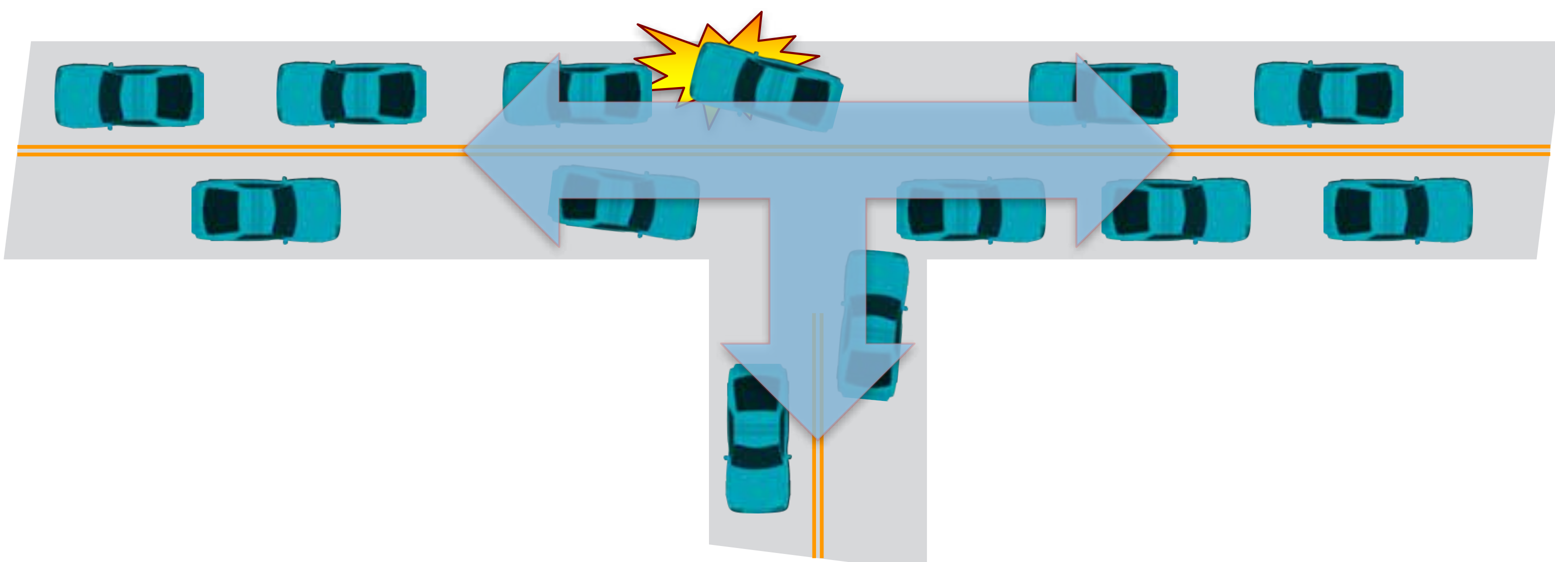




Remaining Problems

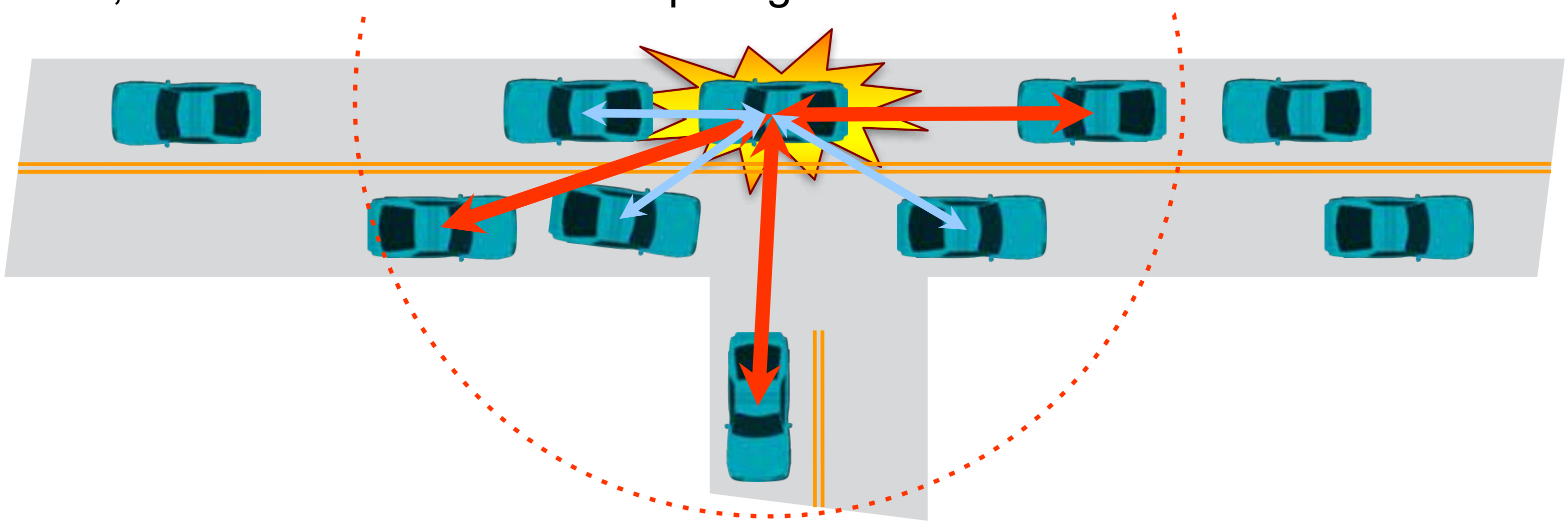
- Temporary network fragmentation

- Undirected message dissemination



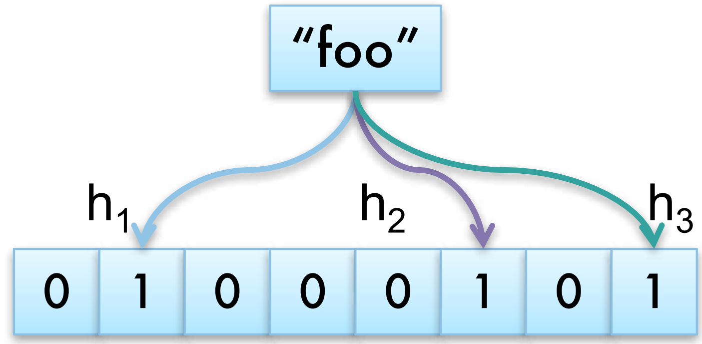
Geocast

- TO-GO
  - “Topology-Assisted Geo-Opportunistic Routing”
  - Nodes periodically send *Hello* beacons; Contents:
    - Number of neighbors
    - Bloom filter of neighbor IDs
    - IDs of neighbors furthest down the road/roads
  - Thus, nodes know about all 2-hop neighbors



[1] Lee, K.C. and Lee, U. and Gerla, M., "Geo-Opportunistic Routing for Vehicular Networks," IEEE Communications Magazine, vol. 48 (5), pp. 164-170, May 2010

Geocast

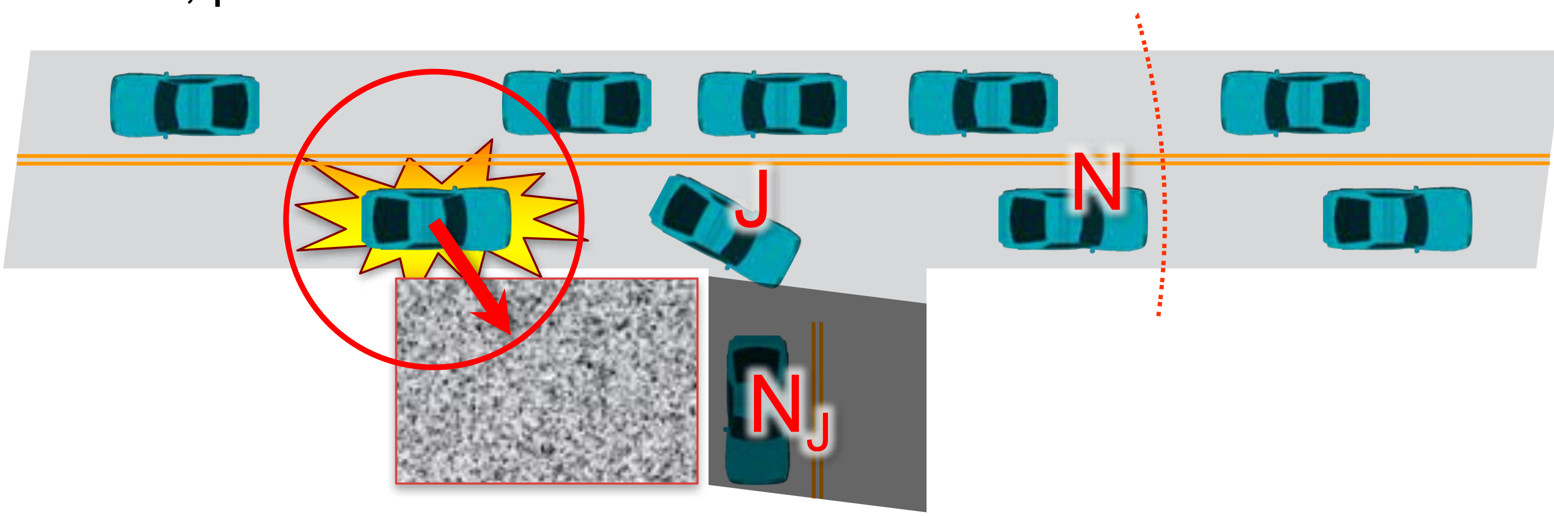


- Bloom Filter
  - Idea:
    - Bloom filter is a bit field X
    - Hash functions h_1 to h_k map input data x → one bit (each) in X
    - Insertion of x: Set $X[h_i(x)] \leftarrow 1 \quad \forall i \in [1..k]$
    - Test for $x \in X$: Check $X[h_i(x)] \stackrel{?}{=} 1 \quad \forall i \in [1..k]$
  - Probabilistic test for "$x \in X$"
    - Possible results: no / maybe (→ chance of false positives)
  - Allows for very compact representation of X

[1] Bloom, Burton H., "Space/time trade-offs in hash coding with allowable errors," Communications of the ACM, vol. 13 (7), pp. 422-426, 1970

Geocast

- TO-GO
  - Find best next hop (Target Node, T)
    - Find N: Furthest neighbor towards destination
    - Find J: Furthest neighbor towards destination, currently on junction
    - Find N_J: Furthest neighbor towards destination, as seen by J
    - if N, N_J are on the same road (and running in greedy mode),
      pick N
      else, pick J



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Case Study: Platooning

Distributed Control
Platooning as one of the most challenging applications

- A specific application: platooning
  - solve traffic congestion problems
  - decrease pollution
  - increase safety
  - decrease severe injuries/deaths
  - Avoid wasting driving time

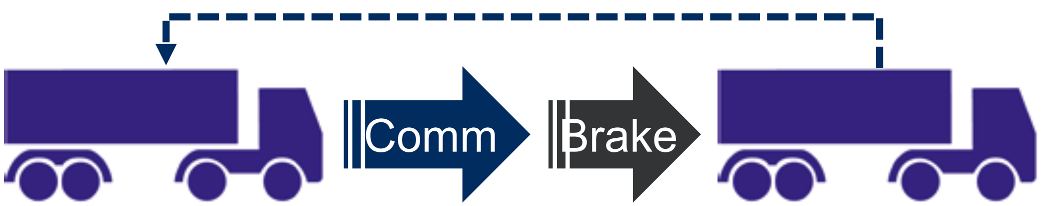
- Research questions
  - Impact of platooning on network (and vice versa)
  - Develop protocols to better support platooning

Automated Car Following

- Manual driving (Dist: 2s ~ 50m @ 100km/h)

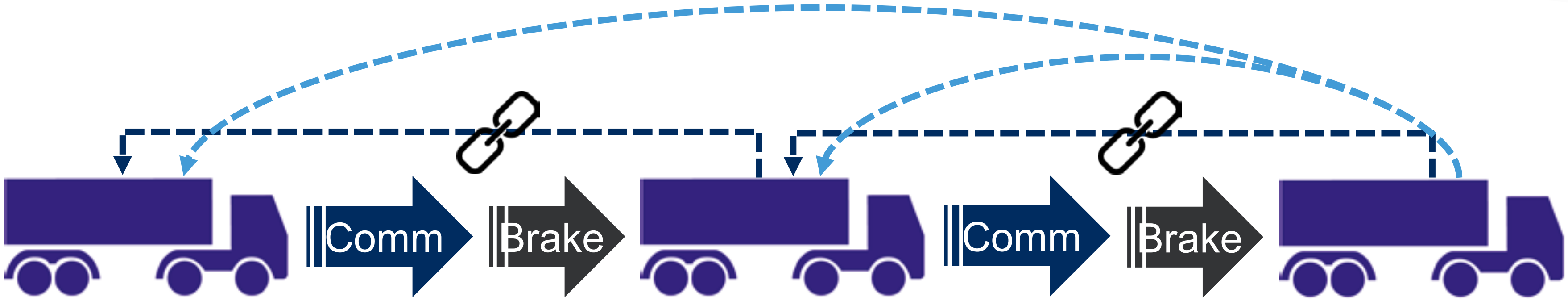
- ACC – Radar based (Dist: 1s ~ 28m @ 100km/h)

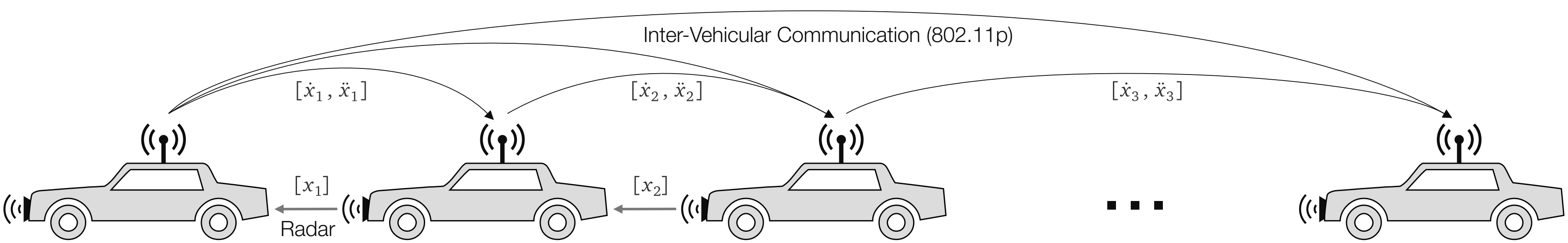
- Simple CACC – Radar + IVC (Dist: 0.6s ~ 16m @ 100km/h)



CACC / Platooning Controller

- Cooperative CACC (Dist: 0.2s ~ 5m @ 100km/h)



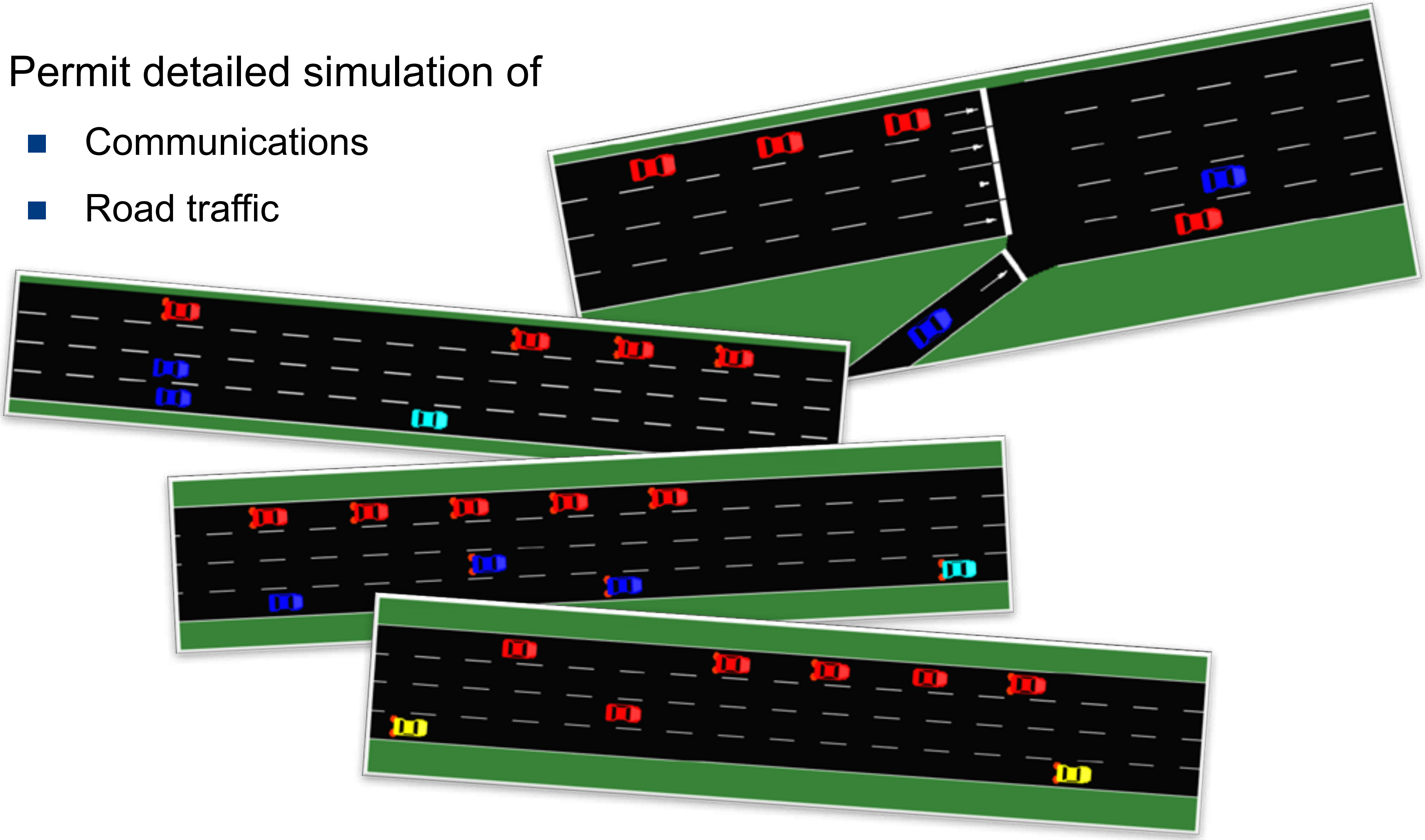


$$\ddot{x}_{i\_des} = \alpha_1 \ddot{x}_{i-1} + \alpha_2 \ddot{x}_l + \alpha_3 (\dot{x}_i - \dot{x}_{i-1}) + \alpha_4 (\dot{x}_i - \dot{x}_l) + \alpha_5 x_i$$

Michele Segata, Bastian Bloessl, Stefan Joerer, Christoph Sommer, Mario Gerla, Renato Lo Cigno and Falko Dressler, "Towards Communication Strategies for Platooning: Simulative and Experimental Evaluation," *IEEE Transactions on Vehicular Technology*, vol. 64 (12), pp. 5411-5423, December 2015.

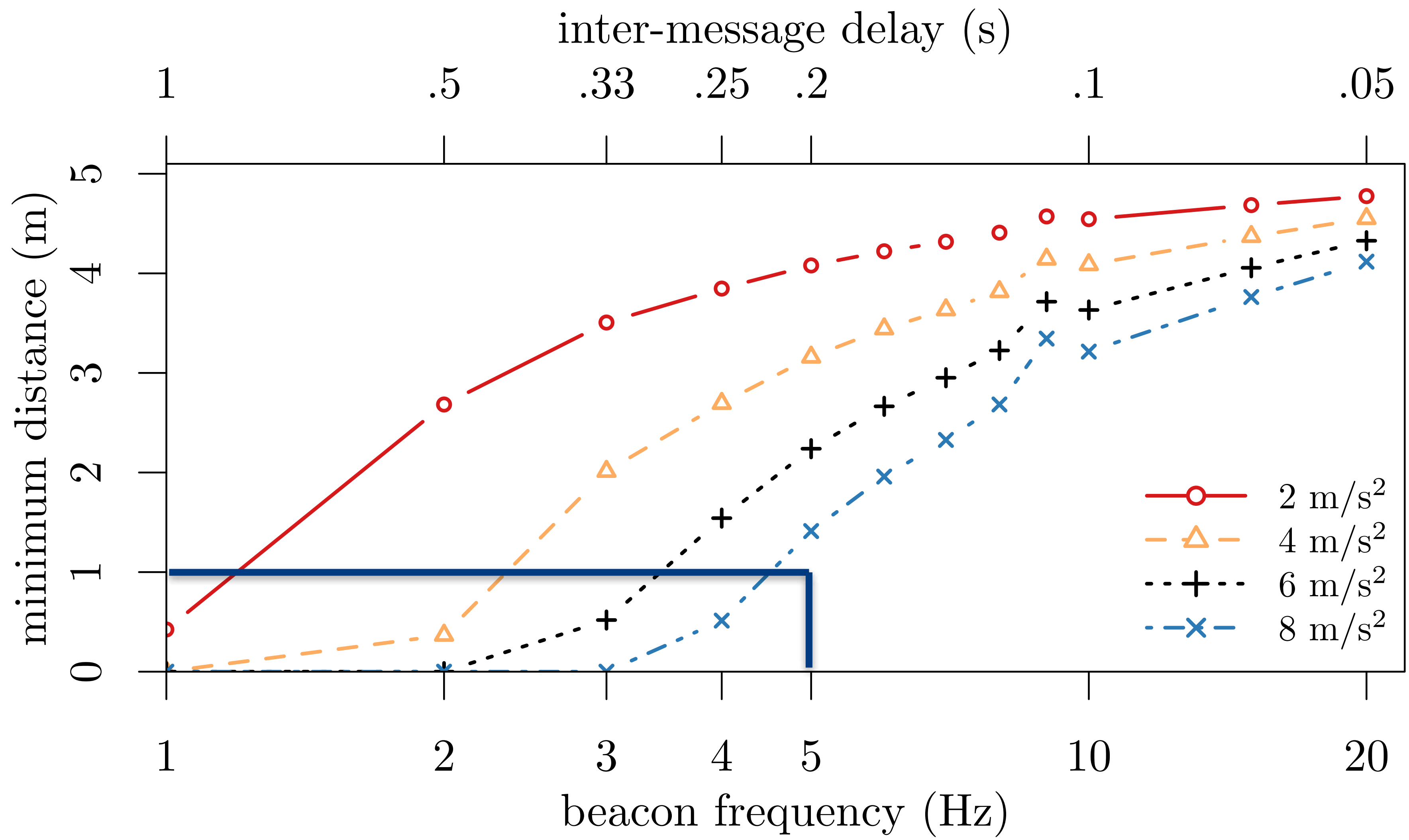
Simulation Framework

- Permit detailed simulation of
  - Communications
  - Road traffic



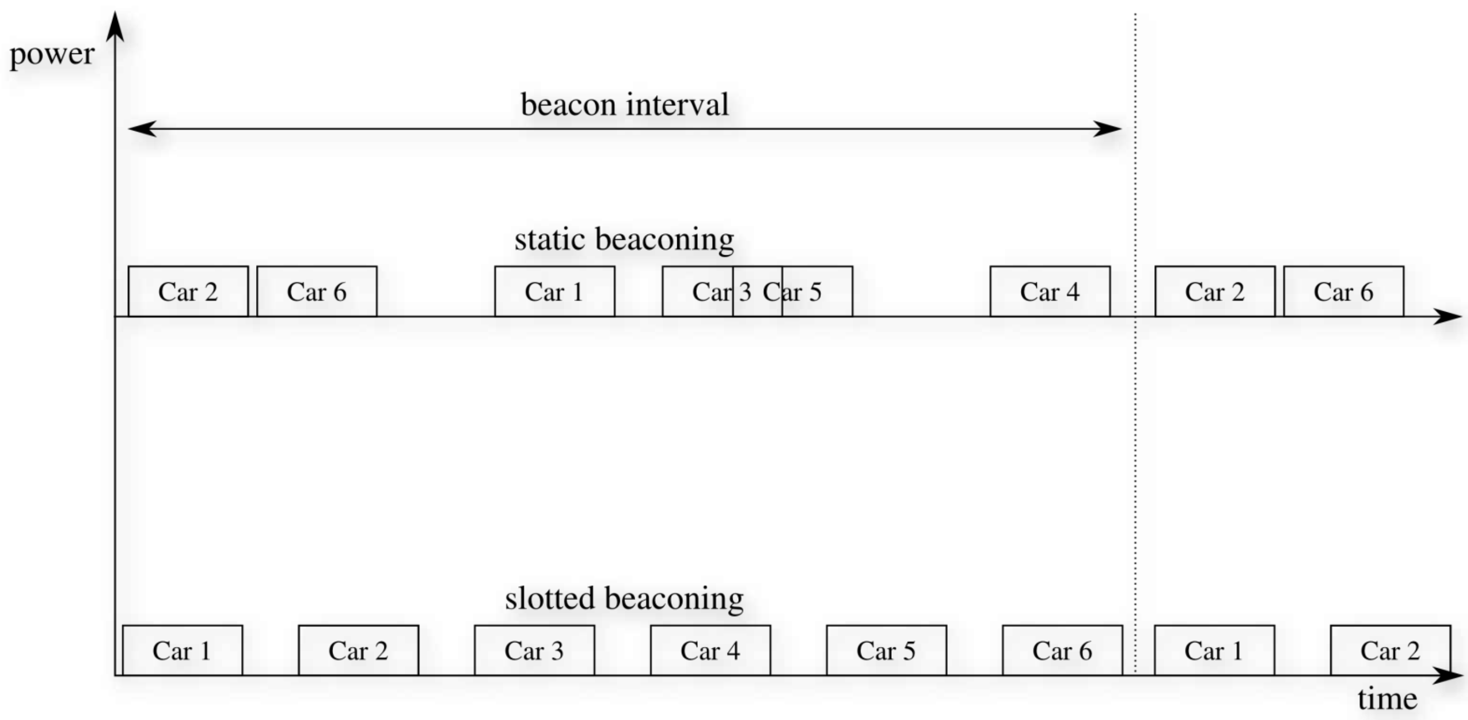
Michele Segata, Stefan Joerer, Bastian Bloessl, Christoph Sommer, Falko Dressler and Renato Lo Cigno, "PLEXE: A Platooning Extension for Veins," Proceedings of 6th IEEE Vehicular Networking Conference (VNC 2014), Paderborn, Germany, December 2014, pp. 53-60.

Platooning Braking – Minimum Distance

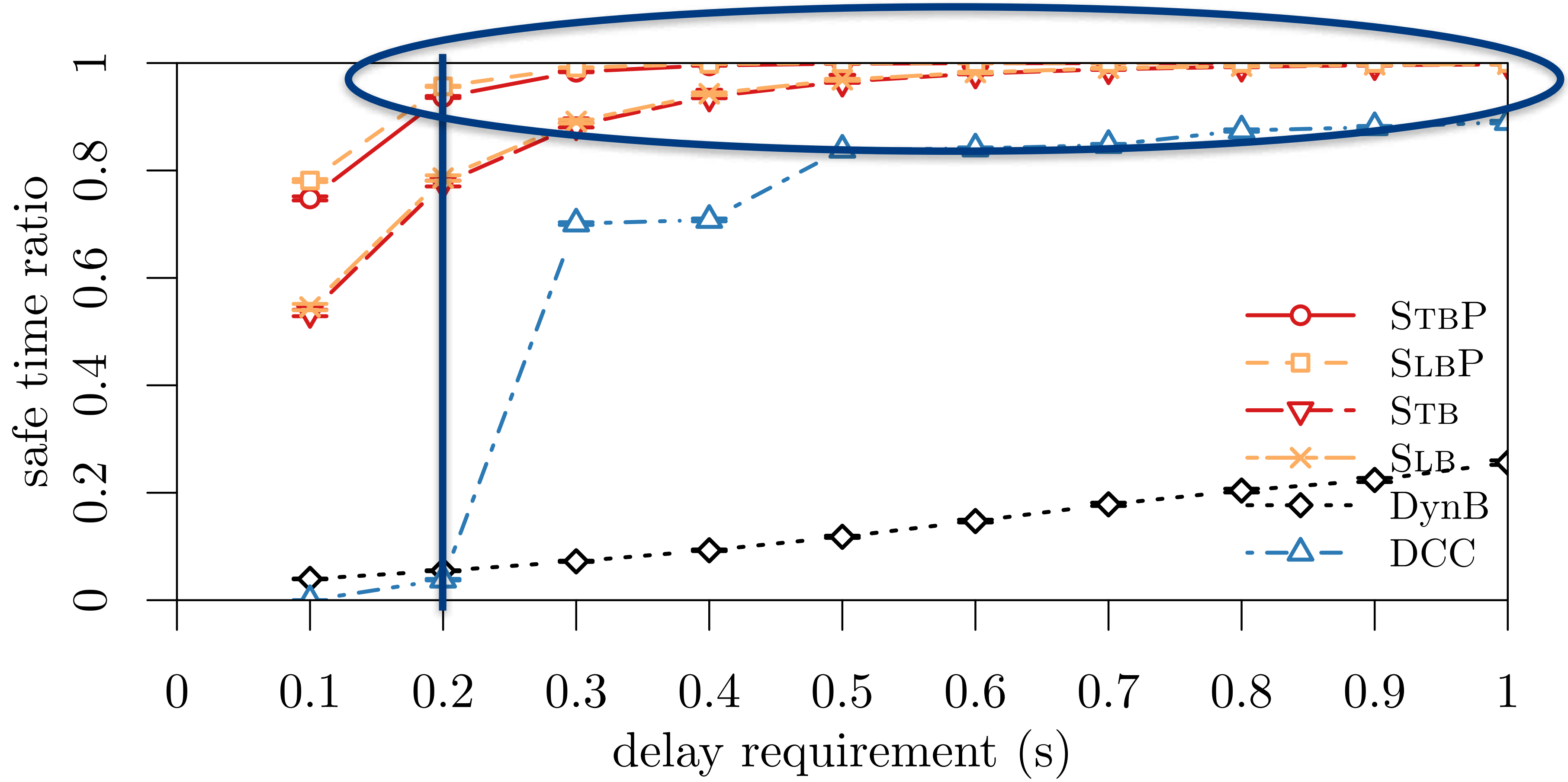


Communication Protocols

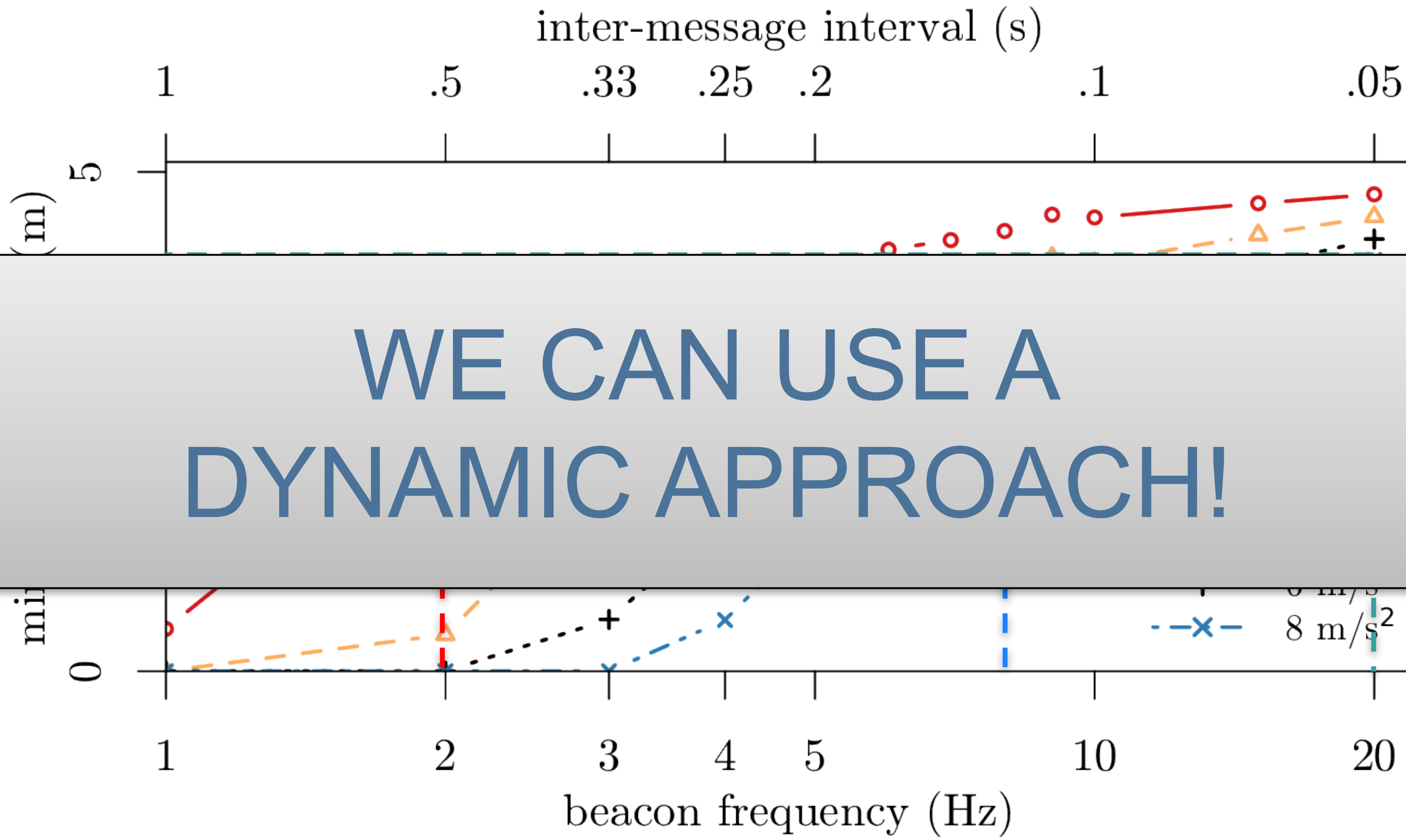
- Develop and test 4 different protocols
  - Random transmission (static beaconing)
  - Synchronized transmission (slotted beaconing)
  - Both w/ and w/o transmission power control



Protocol Performance for 640 Cars



Emergency Braking Requirements



WE CAN USE A DYNAMIC APPROACH!

Jerk: The Concept

- Main idea:
  - the more constant the system, the lower the requirement
  - send updates only when needed, use prediction otherwise

$$v(t) = v(t_{\text{sent}}) + a(t_{\text{sent}}) \cdot (t - t_{\text{sent}})$$

- Problems:
  - awareness: we can't simply stop beaconing
  - what does it mean "constant"?

Michele Segata, Falko Dressler and Renato Lo Cigno, "Jerk Beaconing: A Dynamic Approach to Platooning," Proceedings of 7th IEEE Vehicular Networking Conference (VNC 2015), Kyoto, Japan, December 2015, pp. 135-142.

Jerk Beaconing

- Jerk:
  - physical quantity measuring variation of acceleration over time

$$\Delta_a = a(t) - a(t_{\mathrm{sent}})$$

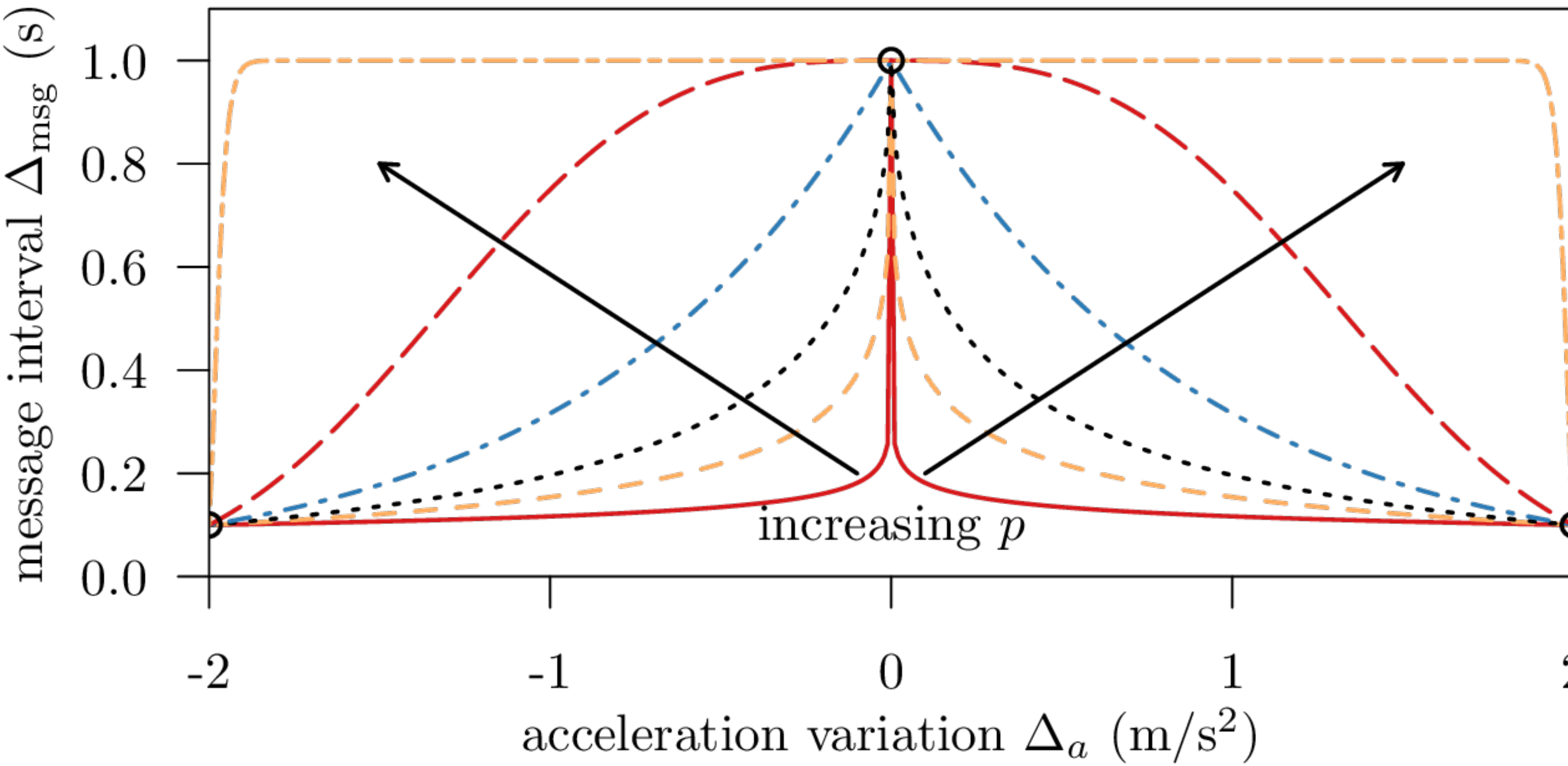
  - using an estimation of jerk we compute the beacon interval

$$\Delta_{\mathrm{msg}}(\Delta_a) = \max\left(e^{-\alpha|\Delta_a|^p} \cdot \max_{\mathrm{bi}}, \min_{\mathrm{bi}}\right)$$

  - tunable parameters:
    - minimum beacon interval
    - maximum beacon interval
    - sensitivity

Jerk Beaconing

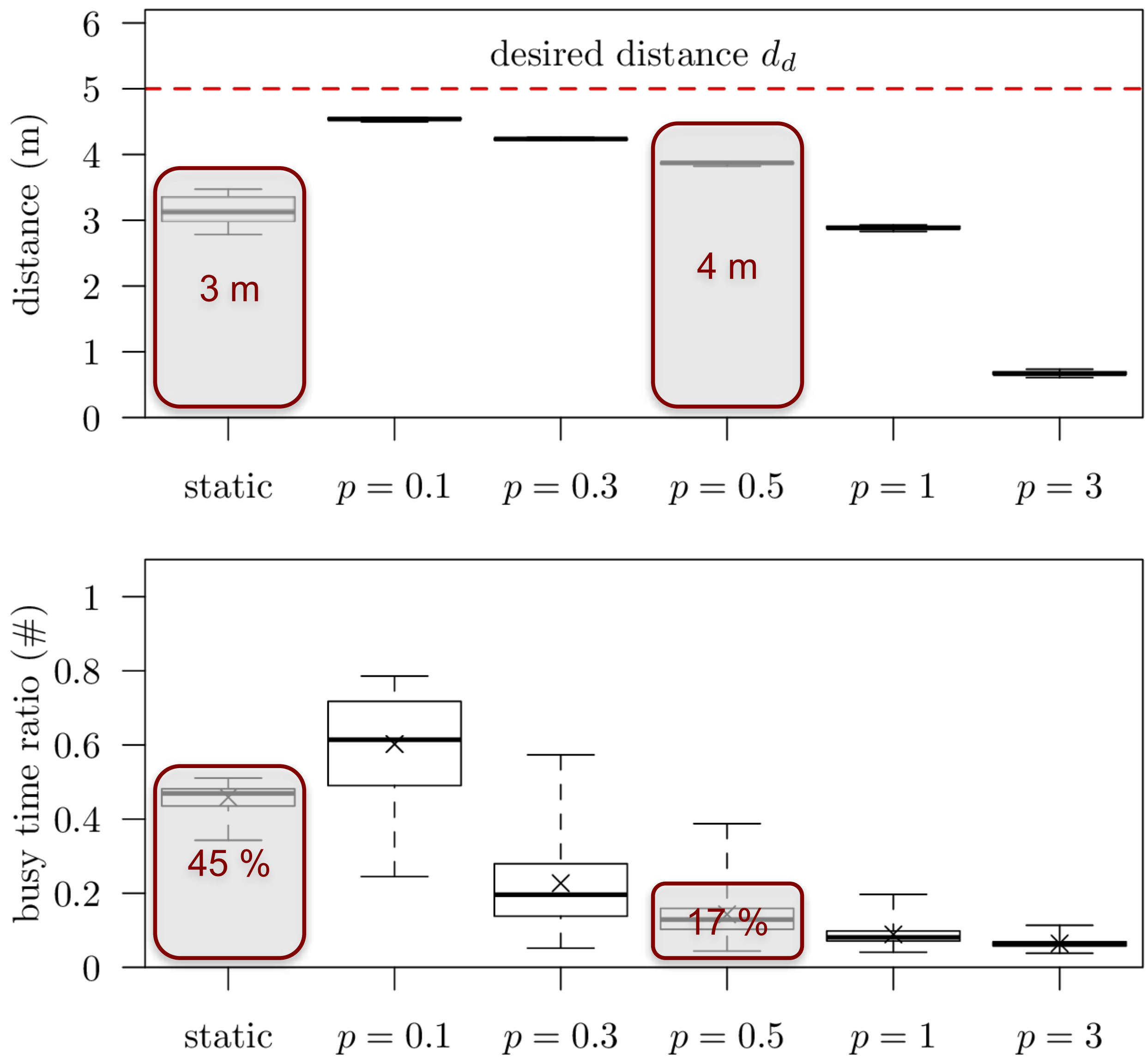
$$\Delta_{\text{msg}}(\Delta_a) = \max\left(e^{-\alpha|\Delta_a|^p} \cdot \max_{\text{bi}}, \min_{\text{bi}}\right)$$



Jerk Beaconing: Reliability

- Problem:
  - (dynamically) undersampling a system → risk in case of losses
- Solution: couple with a reliable delivery mechanism
  - send packets in a chained fashion
  - use transmit power control to increase spatial re-use
    - static assignment
  - piggyback acknowledgements
    - ensure delivery OR
    - try again OR
    - notify application about failure (stop simulation and log outcome)
  - re-propagate leader information (most important)

Protocol Performance for 640 Cars – Harsh scenario



Next Steps

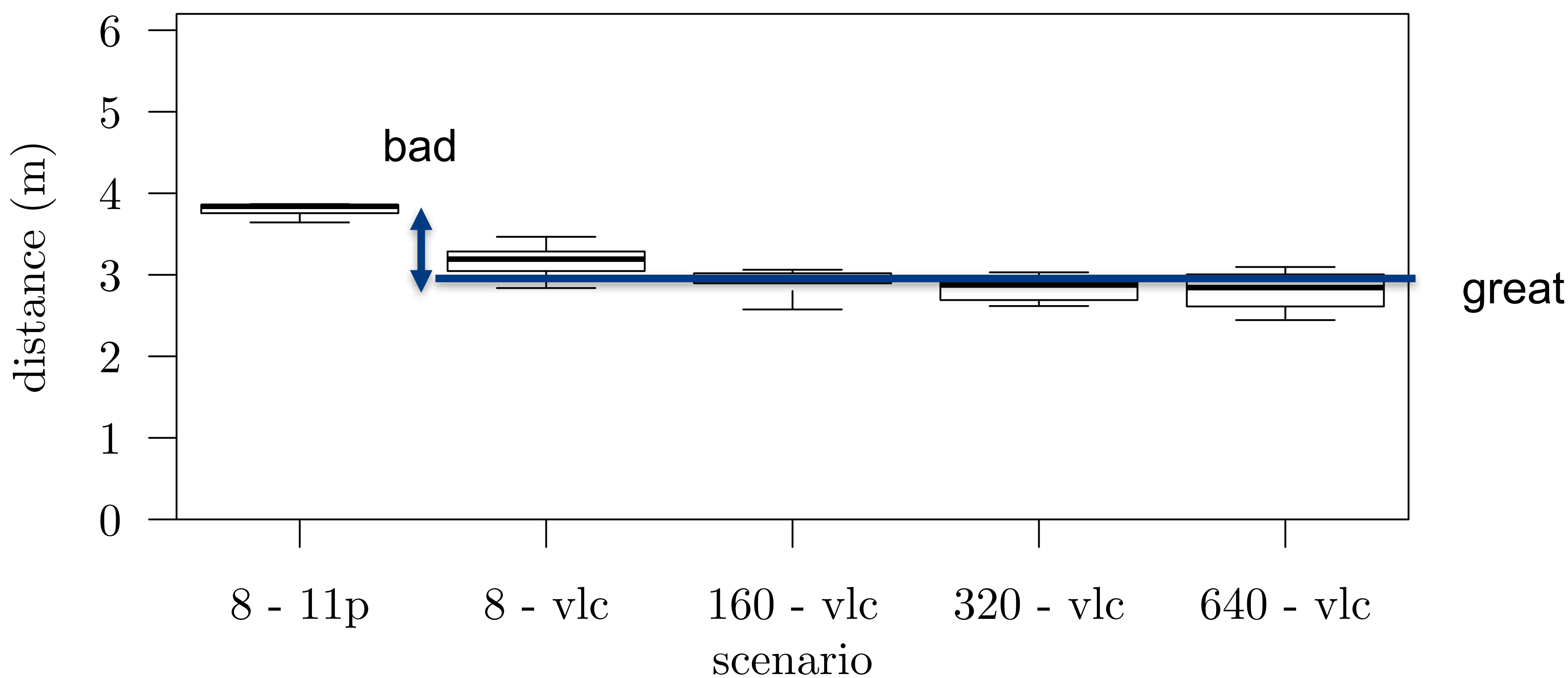
- There's life after static beaconing even for platooning, but
  - jerk beaconing still a heuristic proof of concept
  - can we theoretically link control requirements, beacon interval, and inter-vehicle gap? → optimal beacon rate for target requirement
  - how can we handle network failures?

- **More Options: Getting Heterogeneous**
  - Communication between platoon lead and all followers: **radio broadcast**
  - Communication between succeeding cars: **visual light communication (VLC)**
  - Simple VLC model:
    - Constant (processing) delay
    - 20% packet loss

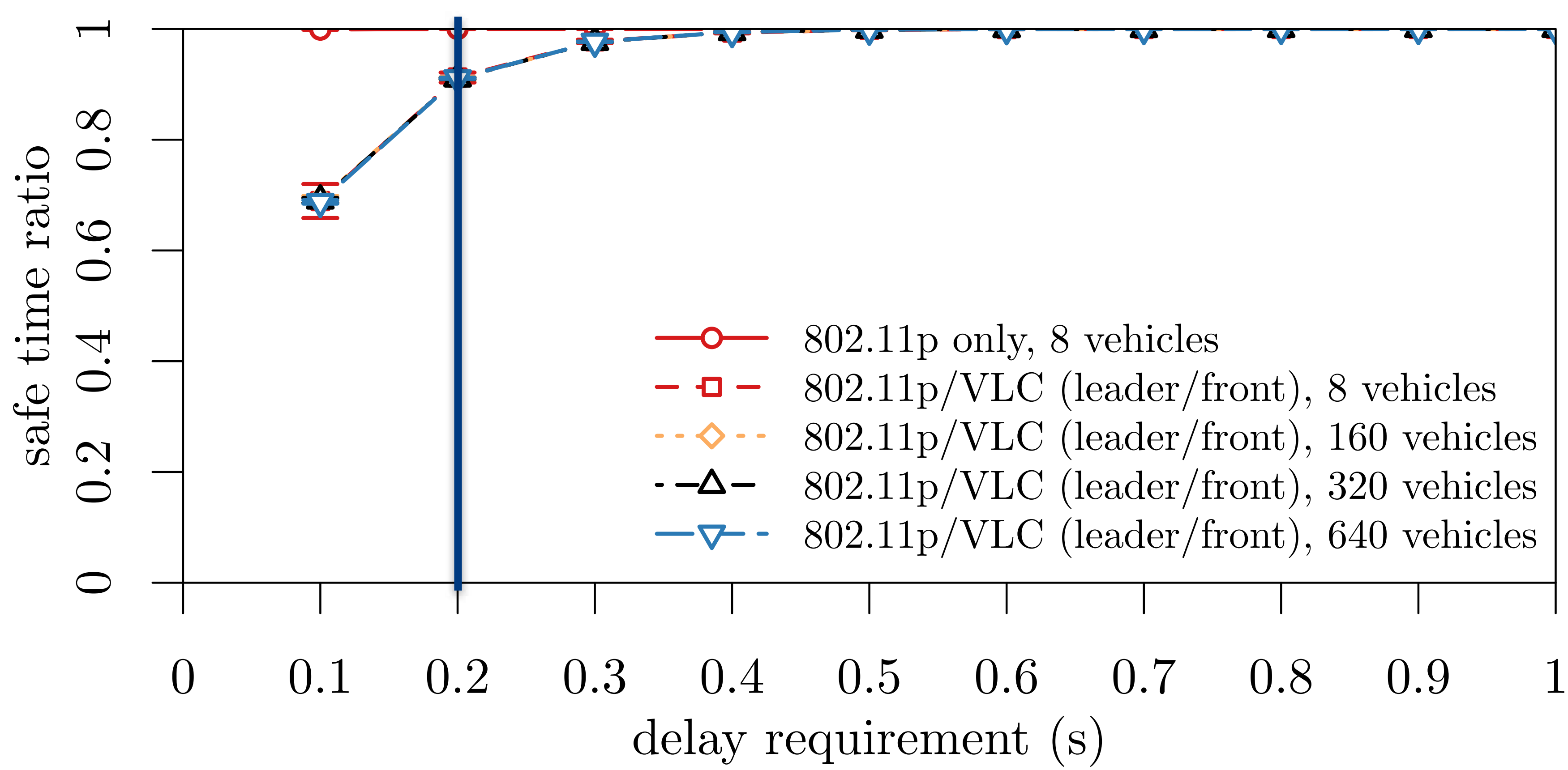
Michele Segata, Renato Lo Cigno, Hsin-Mu Tsai and Falko Dressler, "On Platooning Control using IEEE 802.11p in Conjunction with Visible Light Communications," Proceedings of 12th IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS 2016), Cortina d'Ampezzo, Italy, January 2016, pp. 124-127.

Impact of Using VLC

- LED transmitter, CCD receiver



Protocol Performance with VLC



Performance Evaluation

Evaluation

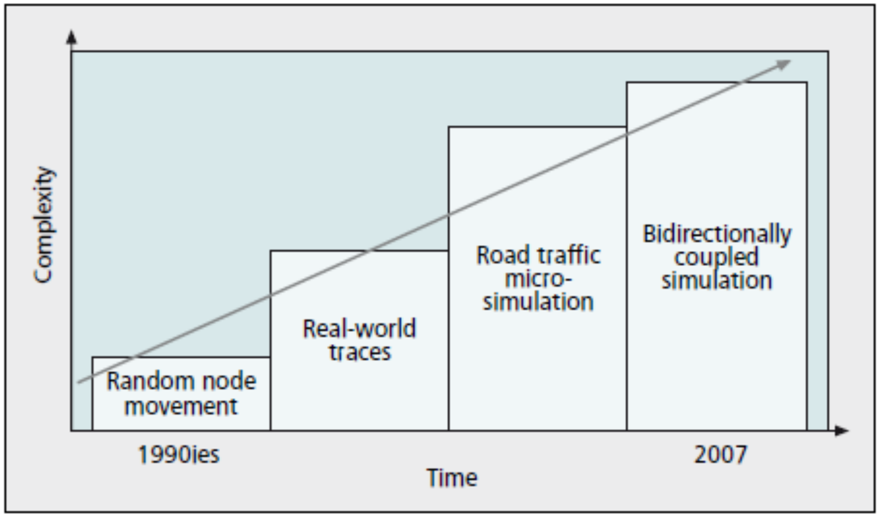
- Real-world experiments
  - Outline only limited information about the feasibility and the performance

    → experiments with roughly 400 cars are planned in a German project
  - Performance evaluation for 2%, 10%, 50%,… penetration?

- Simulation
  - Usually using standard network simulation methods
    - ns2/ns3, OMNeT++, GloMoSim, OPNET, …
  - Detailed network layers, simple “support” modules
  - ***Appropriate for VANETs?***

- Research challenge: appropriate mobility modeling

Mobility Modeling



- Early approaches
  - Random Waypoint
  - Manhattan Grid
  - Traces
- Road traffic microsimulation
  - Simulation of individual cars
  - Exact modeling of streets, speed limits, etc.
- Coupling with network simulation
  - Pre-computation (or on-demand simulation) of road traffic
  - Incorporation of computed traces into network simulators (can be used for real-world traces as well)

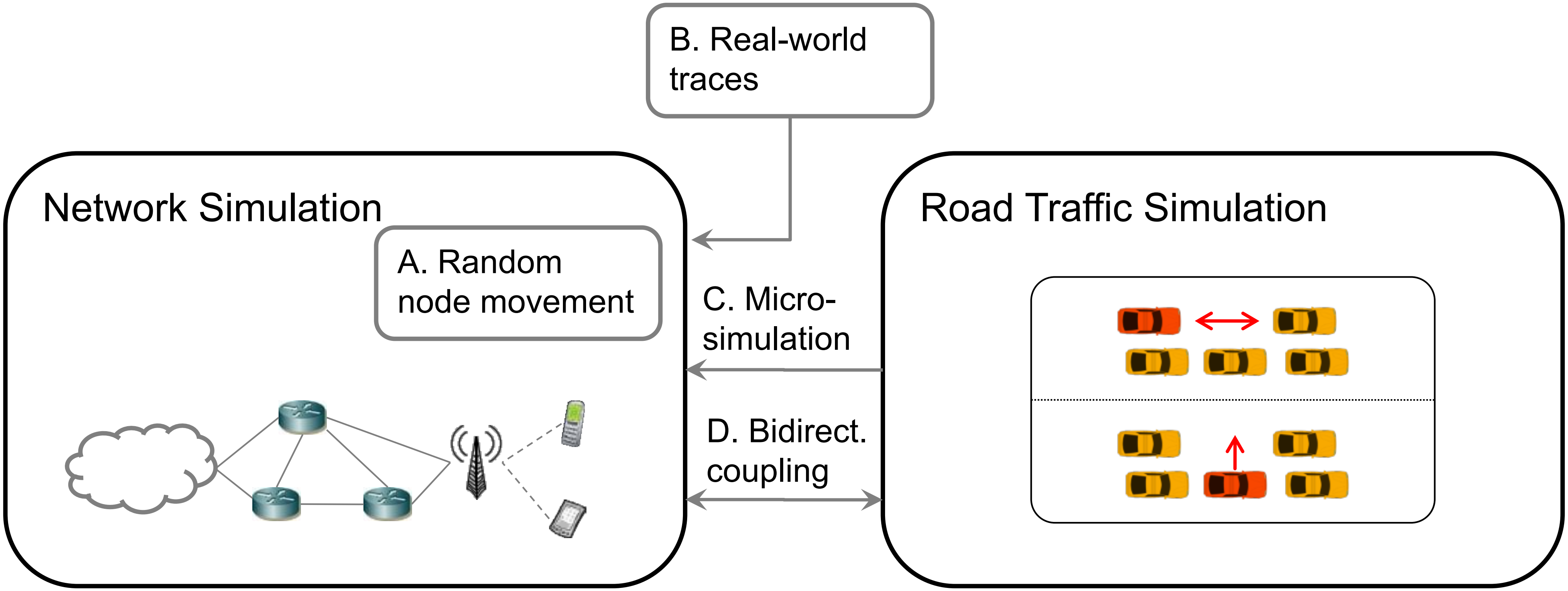
[1] C. Sommer and F. Dressler, "Progressing Towards Realistic Mobility Models in VANET Simulations," IEEE Communications Magazine, vol. 46 (11), pp. 132-137, November 2008

[2] J. Yoon, M. Liu, and B. Noble, "Random waypoint considered harmful," Proceedings of 22nd IEEE Conference on Computer Communications (IEEE INFOCOM 2003), vol. 2, San Francisco, CA, March 2003, pp. 1312-1321

[3] V. Naumov, R. Baumann, and T. Gross, "An evaluation of inter-vehicle ad hoc networks based on realistic vehicular traces," Proceedings of 7th ACM International Symposium on Mobile Ad Hoc Networking and Computing (ACM Mobihoc 2006), Florence, Italy, March 2006, pp. 108-119

Coupling Approaches

- Unidirectional coupling: models road traffic without any optimization through TIS information
- **Bidirectional coupling is important to analyze effects of IVC on road traffic and vice versa**



[1] Christoph Sommer, Reinhard German and Falko Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," IEEE Transactions on Mobile Computing, vol. 10 (1), pp. 3-15, January 2011

[2] M. Treiber, A. Hennecke, and D. Helbing, "Congested Traffic States in Empirical Observations and Microscopic Simulations," Physical Review E, vol. 62, pp. 1805, 2000

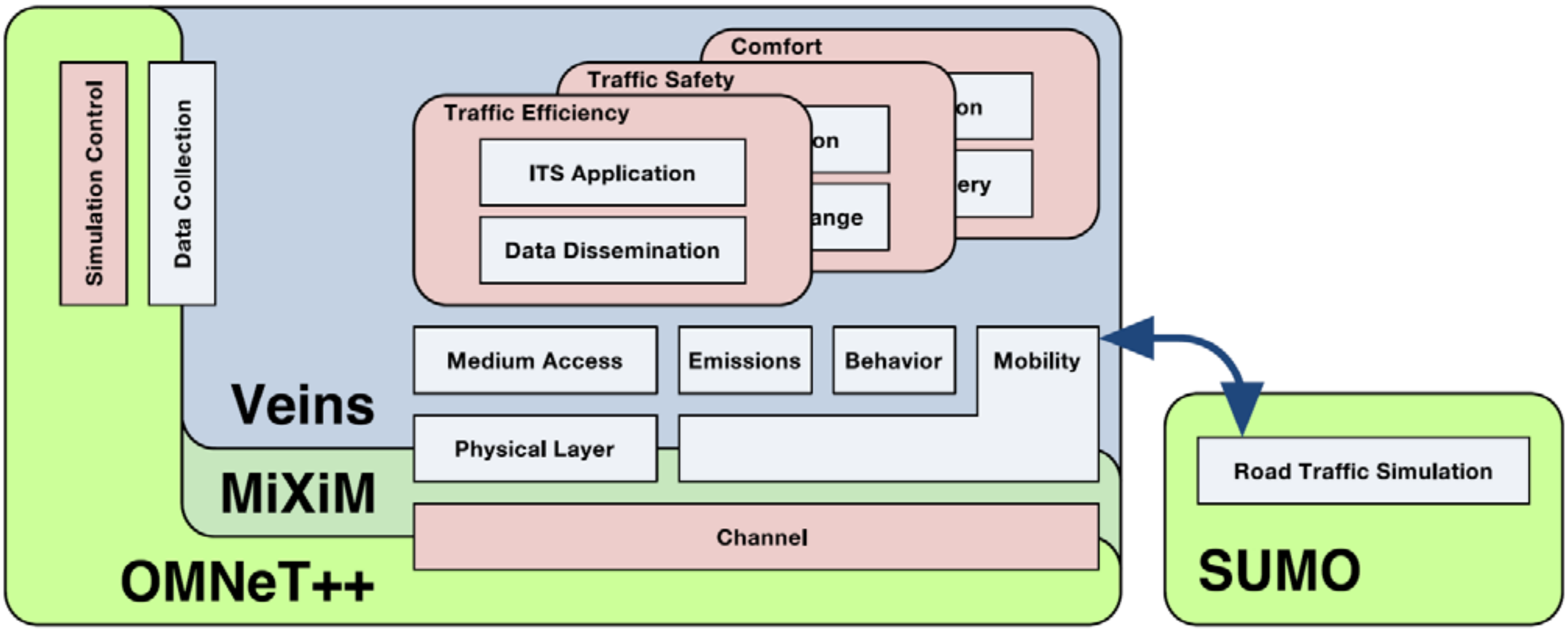
Veins

- Veins – Vehicles in Network Simulation
  - http://veins.car2x.org/
- Based on tools that are well-accepted in their respective communities
  - OMNeT++ for network simulation
  - SUMO for road traffic microsimulation
- Objectives
  - Bidirectionally coupled simulation of VANETs
  - Incorporation of real-world street maps
  - Flexible and fast(!) simulation

[1] Christoph Sommer, Reinhard German and Falko Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," IEEE Transactions on Mobile Computing, vol. 10 (1), pp. 3-15, January 2011

Veins System Architecture

http://veins.car2x.org



[1] Christoph Sommer, Reinhard German and Falko Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," IEEE Transactions on Mobile Computing, vol. 10 (1), pp. 3-15, January 2011

Further Challenges

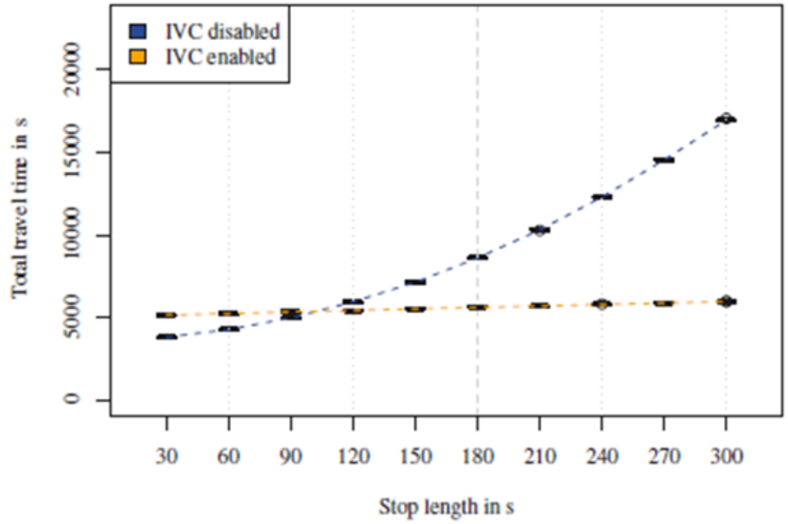
- Evaluation metrics: traveling time vs. CO_2 emission
  - Quite accurate gas consumption / emission models available
  - E.g., EMIT

factor		value	unit
v	vehicle speed		$\mathrm{m\,s^{-1}}$
a	vehicle acceleration		$\mathrm{m\,s^{-2}}$
A	rolling resistance	0.1326	$\mathrm{kW\,m^{-1}\,s}$
B	speed-correction to rolling resistance	2.7384×10^{-3}	$\mathrm{kW\,m^{-2}\,s^2}$
C	air drag resistance	1.0843×10^{-3}	$\mathrm{kW\,m^{-3}\,s^3}$
M	vehicle mass	1.3250×10^3	kg
g	gravitational constant	9.81	$\mathrm{m\,s^{-2}}$
ϑ	road grade	0	degrees
α		1.1100	$\mathrm{g\,s^{-1}}$
β		0.0134	$\mathrm{g\,m^{-1}}$
δ		1.9800×10^{-6}	$\mathrm{g\,m^{-3}\,s^2}$
ζ		0.2410	$\mathrm{g\,m^{-2}\,s^2}$
α'		0.9730	$\mathrm{g\,s^{-1}}$

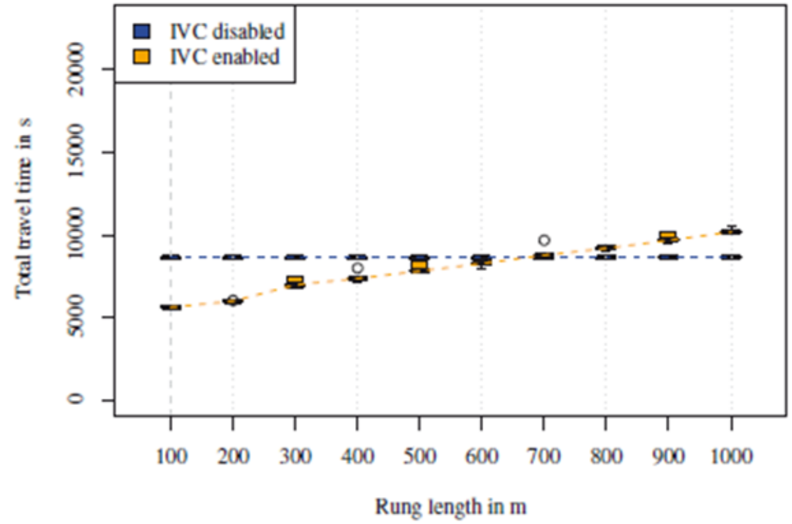
[1] A. Cappiello, I. Chabini, E. Nam, A. Lue, and M. Abou Zeid, “A statistical model of vehicle emissions and fuel consumption,” 5th IEEE International Conference on Intelligent Transportation Systems (IEEE ITSC), pp. 801–809, 2002

[2] C. Sommer, R. Krul, R. German, and F. Dressler, "Emissions vs. Travel Time: Simulative Evaluation of the Environmental Impact of ITS," Proceedings of 71st IEEE Vehicular Technology Conference (VTC2010-Spring), Taipei, Taiwan, May 2010

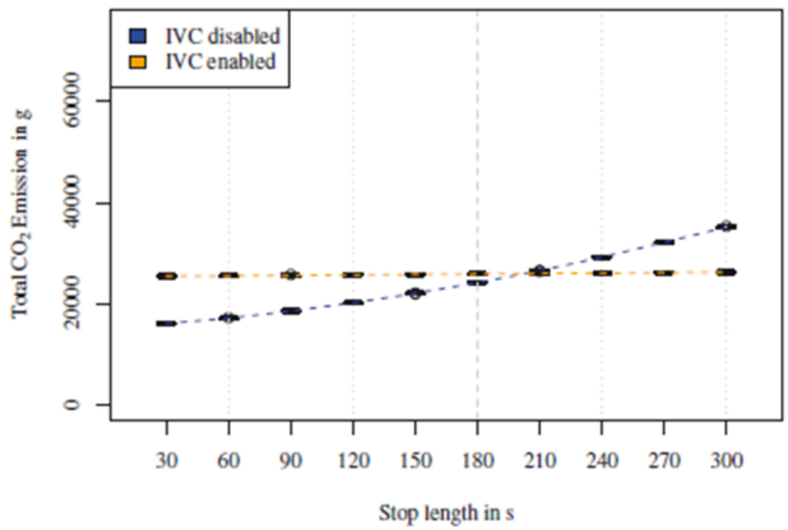
Traveling Time vs. CO_2 Emission



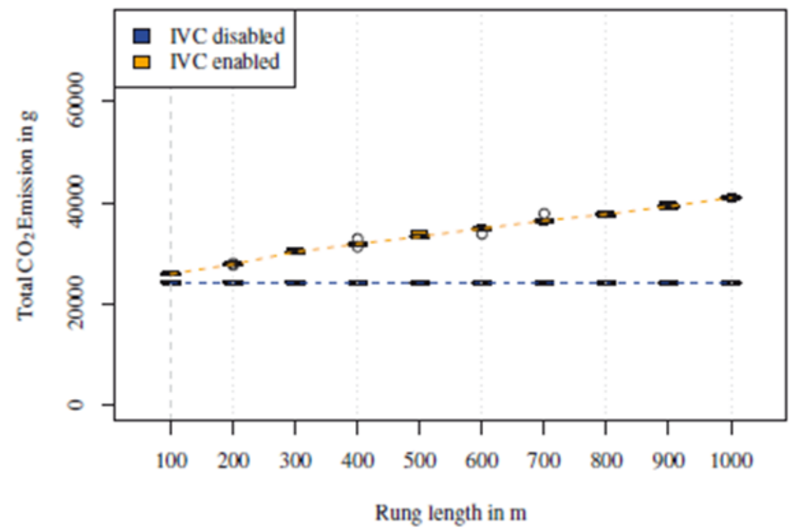
(a) influence of stop length on travel time; 100 m rungs



(b) influence of rung length on travel time; 180 s stops



(c) influence of stop length on emissions; 100 m rungs



(d) influence of rung length on emissions; 180 s stops

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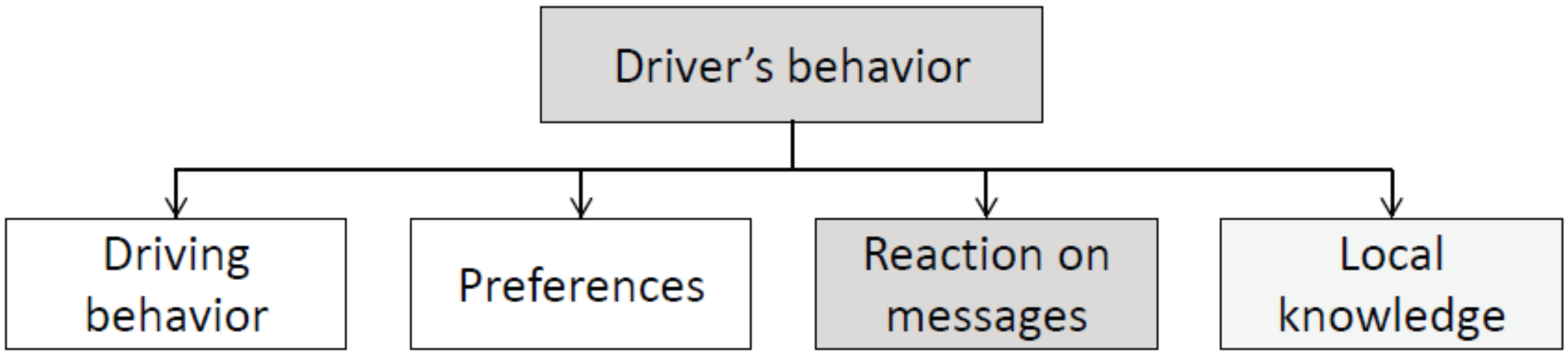
Further Challenges

- Accuracy of technically optimal solutions and imperfect driver behavior



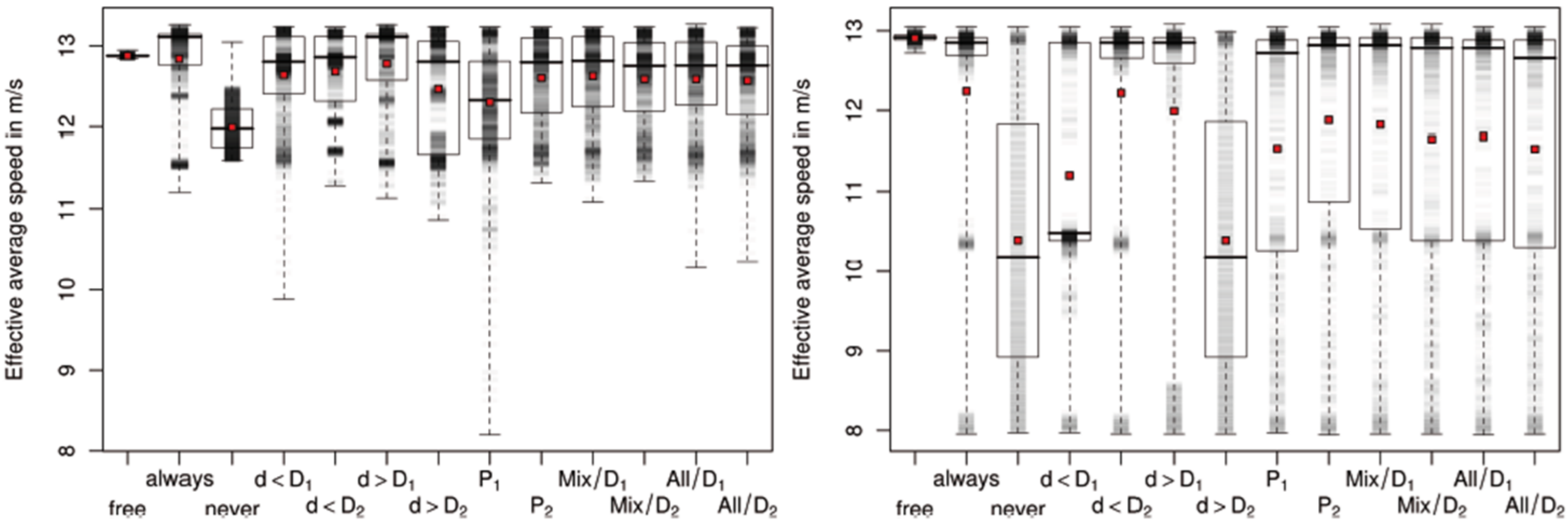
[1] R. König, A. Saffran, and H. Breckle, "Modelling of drivers' behaviour," in Vehicle Navigation and Information Systems Conference, Yokohamashi, Japan, August/September 1994, pp. 371–376.

[2] W. Barfield, M. Haselkorn, J. Spyridakis, and L. Conquest, "Commuter Behavior and Decision-Making: Designing Motorist. Information Systems," in 33rd Human Factors and Ergonomics Society Annual Meeting, Santa Monica, CA, 1989, pp. 611–614.

[3] P. C. Cacciabue, Ed., Modelling Driver Behaviour in Automotive Environments: Critical Issues in Driver Interactions with Intelligent Transport Systems. Springer, 2007.

[4] F. Dressler and C. Sommer, "On the Impact of Human Driver Behavior on Intelligent Transportation Systems," Proceedings of 71st IEEE Vehicular Technology Conference (VTC2010-Spring), Taipei, Taiwan, May 2010

Driver Behavior – Results



[1] F. Dressler and C. Sommer, "On the Impact of Human Driver Behavior on Intelligent Transportation Systems," Proceedings of 71st IEEE Vehicular Technology Conference (VTC2010-Spring), Taipei, Taiwan, May 2010

Conclusions

Conclusions

Today, we studied

- Challenges and opportunities of using connected cars concepts
  - Capability to connect everyone and everything
  - Can be seen as a big data storage
  - Help improving our daily road traffic experience and safety

- Not discussed
  - Security issues: Strong debate about privacy vs. security

… as can be seen, there are many open challenges and questions for another decade of interesting research ☺

More Information?

- Vehicular Networking (Cambridge University Press)